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CONTROLLER REQUIREMENTS FOR UNCOUPLED AIRCRAFT MOTION

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The use of uncoupled, six-degree-of-freedom (6-DOF) motion is rapidly becoming state-of-the-art in terms of necessary flight control laws and aerodynamic capability. The next generation of aircraft may use uncoupled, 6-DOF control capability in conjunction with other new technologies such as Integrated Flight-Fire Control (IFFC). In order for these future applications of 6-DOF control to be successful, the pilot must be able to command motion and acceleration magnitudes with sufficiently good system response characteristics to accomplish particular missions or tasks.

The objective of this effort was to develop design criteria and gather appropriate substantiating data for cockpit control devices for 6-DOF motion which will assure compatibility among the pilot, control device(s) and aircraft response and will thus allow efficient implementation of the 6-DOF control capability. The effort was divided into two phases. Phase I consisted of defining existing data on the design of cockpit controllers for 6-DOF

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motion. The application of 6-DOF aircraft motion to aircraft mission requirements was examined. A set of tentative criteria was formulated and test plans developed to gather data necessary to validate and expand the tentative criteria. Following Air Force approval, a simulation was conducted using the motion-based simulator at Wright-Patterson Air Force Base. The results of the simulation were combined with the results of the literature survey to form a set of design guidelines.

Volume I of this report presents the results of the literature survey, summarizes the simulation effort and presents the design criteria. Volume II is a detailed discussion of the simulation and the analysis of the data. The appendices are also included in this Volume.

FOREWORD

The work reported herein was performed during the period from August 1981 to April 1984 under contract F33615-81-C-3605 from the Air Force Wright Aeronautical Laboratories, Air Force Systems Command. The work was completed under Project 2403, Task 05 and submitted April 1984.

The author wishes to express his gratitude to Carl R. Seavers of McDonnell Aircraft Company and R. Wade Allen of Systems Technology Inc. for their assistance in completing the Phase I literature review and mission effectiveness studies. The efforts were essential to the successful completion of Phase I and in establishing the guidelines for the Phase II simulation.

The Phase II simulation was conducted on the Large Amplitude Multimode Aerospace Research Simulator (LAMARS) operated by the Control Synthesis Branch of the Air Force Wright Aeronautical Laboratories with the support of Lear-Siegler, Inc. The personnel of these groups are to be commended for their cooperation and hard work. In particular the author would like to recognize Jim Zeh and Cal Dyer for their efforts. The pilots for the simulation were drawn primarily from the 4950th Test Wing at Wright-Patterson AFB. The efforts of Lt. Col. Bart Tucker in scheduling pilots were greatly appreciated.

The author is grateful for the assistance and support of Wayne Jewell, of Systems Technology Inc., during the simulation. Mr. Jewell was instrumental in defining the target, motion, and atmospheric disturbances and in conducting the spectral analysis of the time history data.

Another group to be recognized are those individuals who served as contract monitors for this effort. Each applied his own unique talents to the problems as they arose. These individuals were Tom Cord, Lt. John Evans and the final monitor, Tom Gentr .

The author would also like to thank John Caton and Bill Moran and the other individuals at McDonnell Aircraft without whose assistance and support this report would not have been possible.

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SUMMARY

The use of uncoupled, six-degree-of-freedom (6-DOF) motion is rapidly becoming state-of-the-art in terms of necessary flight control laws and aerodynamic capability. The next generation of aircraft may use uncoupled, 6-DOF control capability in conjunction with other new technologies such as Integrated Flight-Fire Control (IFFC). In order for these future applications of 6-DOF control to be successful, the pilot must be able to command motion and acceleration magnitudes with sufficiently good system response characteristics to accomplish particular missions or tasks.

The objective of this effort was to develop design criteria and gather appropriate substantiating data for cockpit control devices for 6-DOF motion which will assure compatibility among the pilot, control device(s) and aircraft response and will thus allow efficient implementation of the 6-DOF control capability. The effort was divided into two phases. Phase I consisted of defining existing data on the design of cockpit controllers for 6-DOF motion. The application of 6-DOF aircraft motion to aircraft mission requirements was examined. A set of tentative criteria was formulated and test plans developed to gather data necessary to validate and expand the tentative criteria. Following Air Force approval, a simulation was conducted using the motion-based simulator at Wright-Patterson Air Force Base. The results of the simulation were combined with the results of the literature survey to form a set of design guidelines.

Volume I of this report presents the results of the literature survey, summarizes the simulation effort and presents the design criteria. Volume II is a detailed discussion of the simulation and analysis of the data. The appendices are also included in Volume II.

SECTION I
INTRODUCTION

The use of uncoupled, six-degree-of-freedom (6-DOF) motion is rapidly becoming state-of-the-art in terms of necessary flight control laws and aerodynamic capability, as demonstrated on such aircraft as NC-131 TIFS (total in-flight simulator) and the YF-16 CCV (control configured vehicle). The Flight Dynamics Laboratory's AFTI/F-16, (Advanced Fighter Technology Integration) will apply 6-DOF motion to specific tasks (ground attack, refueling, crosswind landing, etc.) and the next generation of USAF aircraft may use the 6-DOF control capability in conjunction with other new technologies such as Integrated Flight-Fire Control (IFFC). In order for these future applications of 6-DOF control to be successful, the pilot must be able to command motion and acceleration magnitudes with good system response characteristics to accomplish particular missions or tasks. He does this by manipulation of some control device (stick, rudder pedals, etc.), possibly in conjunction with an automatic control mode.

The objective of this effort is to develop design criteria and gather appropriate substantiating data for cockpit control devices for 6-DOF motion. These criteria will be in a form compatible with the proposed MIL STANDARD and HANDBOOK - Flying Qualities of Air Vehicles. The intent is to establish general trends for specification of controller characteristics, rather than optimize a specific design. The criteria will help to assure compatibility among the pilot, control device(s) and aircraft response and will thus allow efficient implementation of the 6-DOF control capability. The results will apply over the range of aircraft classes and tasks where uncoupled, 6-DOF motion is of benefit.

The effort was divided into two phases. Phase I consisted of defining existing data on the design of cockpit controllers for 6-DOF motion and on the application of 6-DOF motion to aircraft mission requirements. This review covered all classes of aircraft except helicopters and V/STOL aircraft. Based on these past experiences, design guidelines and tentative criteria were developed for a number of controllers identified as potentially applicable. In addition, recommendations for controller design, 6-DOF mechanization and potential evaluation tasks were collected. Attention was also given to the areas of pilot workload reduction and display requirements.

The information collected during Phase I was very interesting and potentially useful in planning further research. However, attempts to develop tentative criteria based on a review of the available literature were hampered by the myriad of different controllers used in these studies. Often in these studies the controller characteristics were not described in any detail since the experiments were aimed at proving viability of uncoupled control rather than desirability of the controller. Also, continued references to the inadequacy of controllers in the various references indicate that a satisfactory method has not been found.

For these reasons, a Phase II simulation effort was planned to collect data specifically on the effects of controller variations. While Phase I had covered all classes of airplanes, the simulated configurations concentrated on fighter aircraft response characteristics and tasks. This aircraft type covered the largest range of potential application of 6-DOF control. The evaluation tasks included air-to-ground weapon delivery, STOL fighter approach and landing, and air-to-air tracking.

The simulation was conducted on the Large Amplitude Multimode Aerospace Research Simulator (LAMARS) at Wright-Patterson AFB, Dayton, Ohio. LAMARS is a beam-type, motion-base simulator. A simplified low order simulation method developed by McDonnell Aircraft Company was used to model aircraft conventional and uncoupled responses.

1. DEFINITIONS OF MODES OF MOTION - Some explanations and definitions of uncoupled, 6-DOF aircraft motions are appropriate:

Mode, as used herein, defines the type of aircraft response to a commanded input by the pilot. Most of the modes discussed here have been examined in ground-based or inflight simulations.

Conventional aircraft control is achieved by controlling the moments about three axes (roll, pitch and yaw) and the force along the body axis (thrust/drag modulation). Motion in the two remaining axes is achieved by using the airframe response to moments controllable by the pilot, such as bank-to-turn, lift due to angle of attack, and side-force due to sideslip. Control implementation schemes have been developed to allow control of forces in the vertical and lateral axes. These additional degrees of freedom provide several new control modes. These added modes are identified by the parameter(s) held constant.

a. Longitudinal Modes -

- Vertical path control - Normal load factor (vertical acceleration control) at constant angle of attack.
- Vertical translation - Vertical acceleration/velocity control at constant attitude.
- Fuselage elevation aiming - Fuselage angle of attack control at constant load factor.
- Drag modulation - Velocity control at a constant thrust setting.

- o Maneuver enhancement - Blending of conventional and either vertical path control or vertical translation to provide quicker response and/or improved ride quality.

b. Lateral Modes -

- o Lateral translation - Lateral acceleration/velocity control without yaw rotation or roll motion (i.e., constant heading).

- o Wings level turn - Heading control with no sideslip or roll attitude motion.

- o Fuselage azimuth aiming - Azimuth angle control with no lateral load factor.

SECTION II
LITERATURE SURVEY

A review of the literature pertinent to control devices and uncoupled aircraft motion was conducted during the latter part of 1981. Attempts were made to examine all information available at that time. Over 100 reports and papers were reviewed during this period. Additional reports not directly covered in the literature review are listed in the bibliography. This section discusses the areas covered by the review and comments on the findings.

The results of this survey can be broken into two distinct areas - basic considerations of controller design and operational development and/or test of aircraft having uncoupled motion capability.

1. <u>BASICS OF CONTROLLER DESIGN</u> - Seven basic considerations and principles of aircraft controller designs are:

- o Force-displacement characteristics -- The amount of displacement for a given force, (e.g., nonlinear gradients, breakout forces, force limits).
- o Force feedback and trim cuing -- Control system and surface forces reflected at the controller, (e.g., parallel vs series trim systems, stick shakers, motion stops).
- o Controller input - aircraft response characteristics -- The amount of aircraft response (i.e., pitch rate, normal acceleration, etc.) for a given input to the controller by the pilot (i.e., force or deflection).
- o Harmonization -- The relative force-displacement characteristics between control axes, (e.g., lateral versus longitudinal stick force levels).
- o Motion coupling and disturbance -- Aircraft motions which inertially couple into control axes or interfere with the pilots manipulation, (e.g., bobweight effects producing control cues and commands).
- o Controller/display relationship -- The relationship between controller actions and display response, (e.g., controller logic versus outside-in or inside-out display).
- o Static anthropometric controller characteristics -- The physical size and location of the manipulator with respect to the pilot, (e.g., circumference of the controller compared with the pilot's hand size).

This study will produce requirements for the Military Standard, Flying Qualities of Air Vehicles. Therefore, the last category above will not be of prime importance.

The remaining considerations can be sub-divided into three general categories. The first category is the concern of proprioceptive feedback of information to the pilots. This tells him about the consequence of his controller actions, how these affect the state of the vehicle, and the relative magnitude of these actions with respect to controller thresholds and limits. The second category involves the pilot's biomechanical coupling to the controller. This effectively sets the bandwidth of the pilot's responses and also provides pathways for inertial motions to feedback into the control system. The third general category involves the discrimination between different controller axes. This includes the differentiation required between controller actions in the different axes. Thus, the pilot can make desired controller responses in a chosen control axis and minimize inadvertent cross-coupling control into other axes. The relationship between control responses and various visual motion feedbacks is also part of the third category.

The following section will review literature that relates to the above controller considerations. The fixed-base tracking literature will be discussed to give some feeling for proprioceptive feedback and discrimination considerations in controller design. Subsequent sections will treat biomechanical aspects of actual motion, including feel characteristics and motion feedthrough to the controller. We will discuss sources of disturbances to the pilot's controller manipulation process and will review the modern fly-by-wire sidestick configuration whose design departs from the traditional hydromechanical control systems. Finally, general pilot models will be reviewed that are useful for setting up measurement algorithms for the Phase II simulation.

2. FIXED-BASE TRACKING LITERATURE - Research on controller characteristics dates back to World War II. Early work by Jenkins (Refs. 1-3) for the Army Air Force Air Material Command concerns the accuracy of pilots in applying pressure on hand controllers and rudder pedals. Some reinterpretation of Jenkins' data shows that the pilot's accuracy in applying desired pressures to controllers can be described by the following formula:

Standard Deviation (Accuracy) = $\pm$.25 lbs $\pm$ 5% of required force

In modern terms, the data could probably be reinterpreted in terms of the remnant or motor noise exhibited by the human operator in performing manual control tasks. Much of the fixed-base tracking literature has been organized into bibliographies and the early bibliography by Andreas (Ref. 4) categorizes literature up through 1953. A later bibliography by Muckler (Ref. 5) includes some interpretation of the literature. One comment by Muckler is somewhat typical of a large part of the available tracking literature; "The majority of the studies are isolated empirical demonstrations of the particular phenomena which point to a possibly critical area, yet fail to provide the kind of detailed research data that is necessary for control system design."

Although design guidance for specific operational configurations is often not available, some basic principles have evolved from the tracking literature. Generally, tracking performance improves with increasing stiffness in the control forces. Tracking performance generally degrades when the dynamics of the control task become more complicated, however. Controller characteristics can contribute complication, so for example, performance degrades when excessive controller damping and inertia characteristics act to limit the bandwidth of the pilot's control actions.

Regarding control display relationships, Bernotat (Ref. 6) reports a rather innovative experiment as illustrated in Figure 1. Bernotat employed three different display formats which gave the operator varying amounts of information as to the angle of display response given a specific controller response. Display Format (a) was a pure compensatory display without any additional indication of rotation angle. Subjects were verbally informed about the display rotation angle relative to the control action before the test run started. Display (b) was similar to (a) but with an overlaid coordinate system which indicated the relative display control angle. In the third or Display (c) format, no direct information was given about the relative rotation angle between a display movement and controller action. However, a target symbol included an additional vector, the direction and magnitude of which informed the operator about the direction of display motion he was commanding with a given set of controller actions. The controlled element in Bernotat's task was a pure integrator with an additional time lag. Random noise was fed into the control system parallel with the stick signal and had an upper bandwidth of 1 cycle/sec.

Results in terms of displayed error are illustrated in Figure 2 for the Ref. 6 experiment. For the conventional compensatory display (a), the results were best for either the direct display mode, i.e., 0 and 360 deg display rotations or the 180 deg display rotation implying a negative gain between the controller and display. Display orientations other than these values were decidedly worse in achieved performance levels. On the average, the second display format (b) gave similar results. However, the large maximum error excursions over the rotation range of 90-270 deg would indicate that there were probably occasional control reversals in that region. The third display conditions (c) gave uniformly good performance irrespective of the rotation angle of the display motion relative to controller action. These results indicate that for relatively simple display formats, the display motions should be directly related to controller actions. More sophisticated display formats may permit somewhat arbitrary relationships between a display and controller actions.

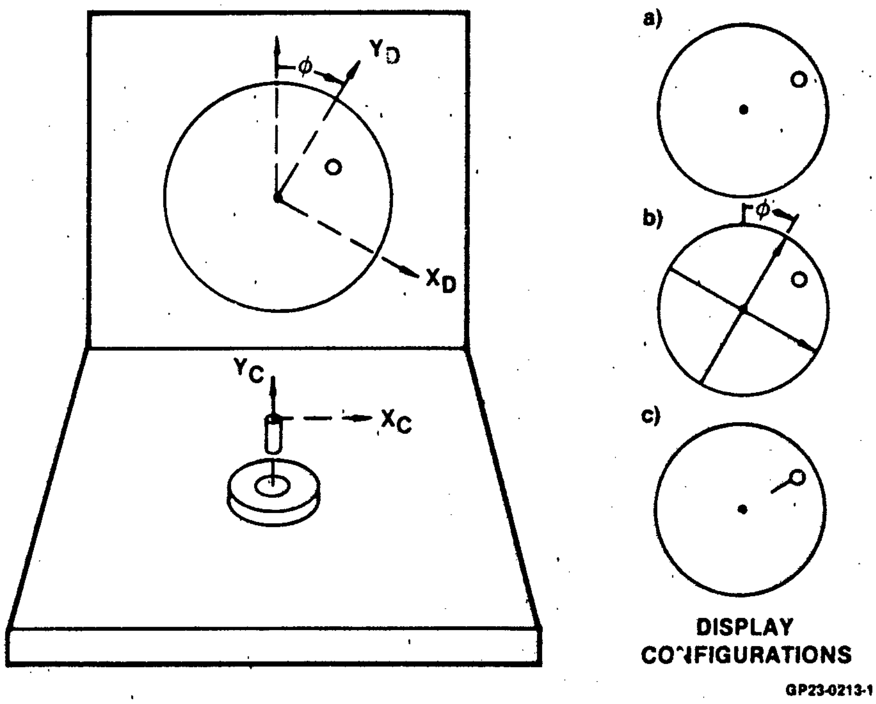


Figure 1. Setup and Display Configurations for Reference 6 Experiment

More recently Merhav and Ya'acov (Ref. 7) have demonstrated a principle of controller characteristics related to the proprioceptive feedback provided by controller actions. This approach based on earlier work by Herzog (Ref. 8) involves torque feedbacks to the controller based on the controlled element dynamics such that the control dynamics appear to be a zero order system. This amounts to a control task giving the same kinesthetic cues as would be involved in the direct handling of objects. This approach has shown that kinesthetic information paths in manual control play an important role in workload reduction, particularly in the case of high order or unstable plants.

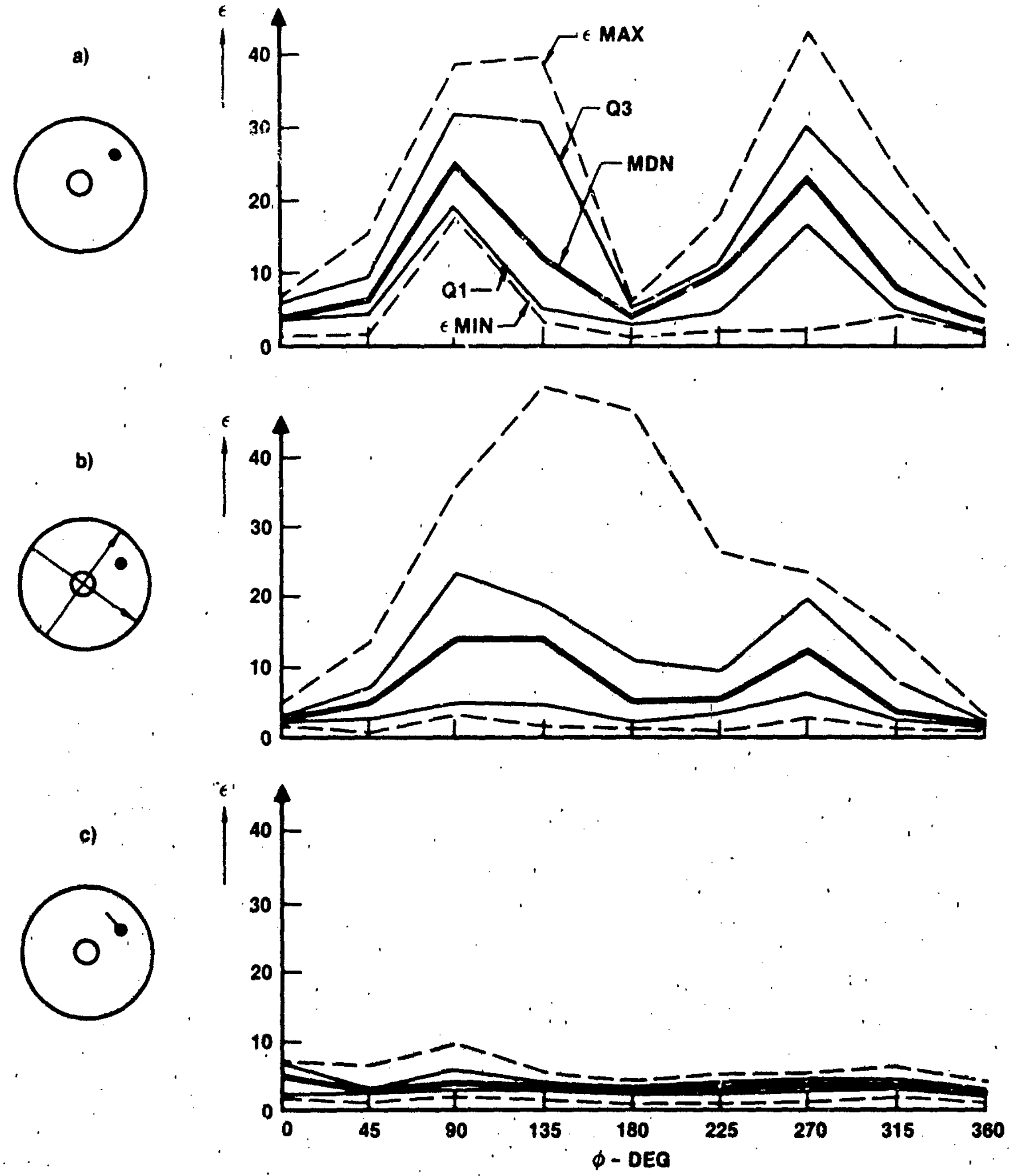


Figure 2. The Influence of Display/Controller Axis Rotation (ϕ) on Tracking Performance (ϵ) in Reference 6 Experiment

At Systems Technology, Inc. (STI) a series of automobile driver performance studies over the past few years has also tended to highlight the importance of kinesthetic cues in achieving improved manual control behavior (Ref 9). Several studies have been performed in a fixed-base driving simulator and also a comparable experiment was conducted in an instrumented car on a closed course test track. Random disturbances were injected into the driver's steering task loop and driver describing function measures were obtained. In Figure 3, we compare driver steering response model parameters for the three fixed-base simulator studies and one in-vehicle study. The STI fixed-base driving simulator has a torque feel system which allows steering torques to be accurately represented to the driver. In the three fixed-base simulator studies the torques at the steering wheel felt by the driver were generated in various ways. One was a simple spring restraint that was strictly proportional to wheel angle. Another was a power steering feel simulation where small perturbations around zero were due to the dynamic torques generated by slip angle of the front wheel. Power steering boosts produced most of the feel for larger slip angles. In the third study, strictly manual feel forces were represented due to the restoring torque characteristics modified by any boost system. In the instrumented car field test the vehicle had a power steering system. However, motion cues were present in this case compared with the fixed-base simulator tests. In Figure 3, note that as the dynamic kinesthetic feel feedback is increased from the pure spring restraint to the manual steering system, the driver's effective time delay in the steering regulation task drops dramatically, and under the manual steering condition is almost equivalent to the time delays measured in the field test with an instrumented vehicle. Note also that the driver's corresponding crossover frequency increases consistent with decreases in time delay. In the field test the driver has a considerably increased crossover frequency probably due to the very tight constraints placed on the test course which included cones on each side of the roadway. The equivalent constraint was not present in the simulator study.

The above research studies show that the feedback of dynamic control information through the kinesthetic senses can have rather dramatic effects on human operator performance. The principle of kinesthetic feedback or cuing is interesting in light of the current trend to fly-by-wire sticks which can eliminate dynamic feedback to the pilot through the controller. This is an area that definitely deserves further study in terms of operational aircraft piloting tasks.

3. <u>PILOT-CONTROLLER COUPLING</u> - Early work by Magdaleno and McRuer (Refs. 10 and 11) laid the basic foundations for understanding the coupling between the human operator and controller characteristics. In Ref. 10, three manipulators were compared; these were a pressure manipulator, a free-moving manipulator and

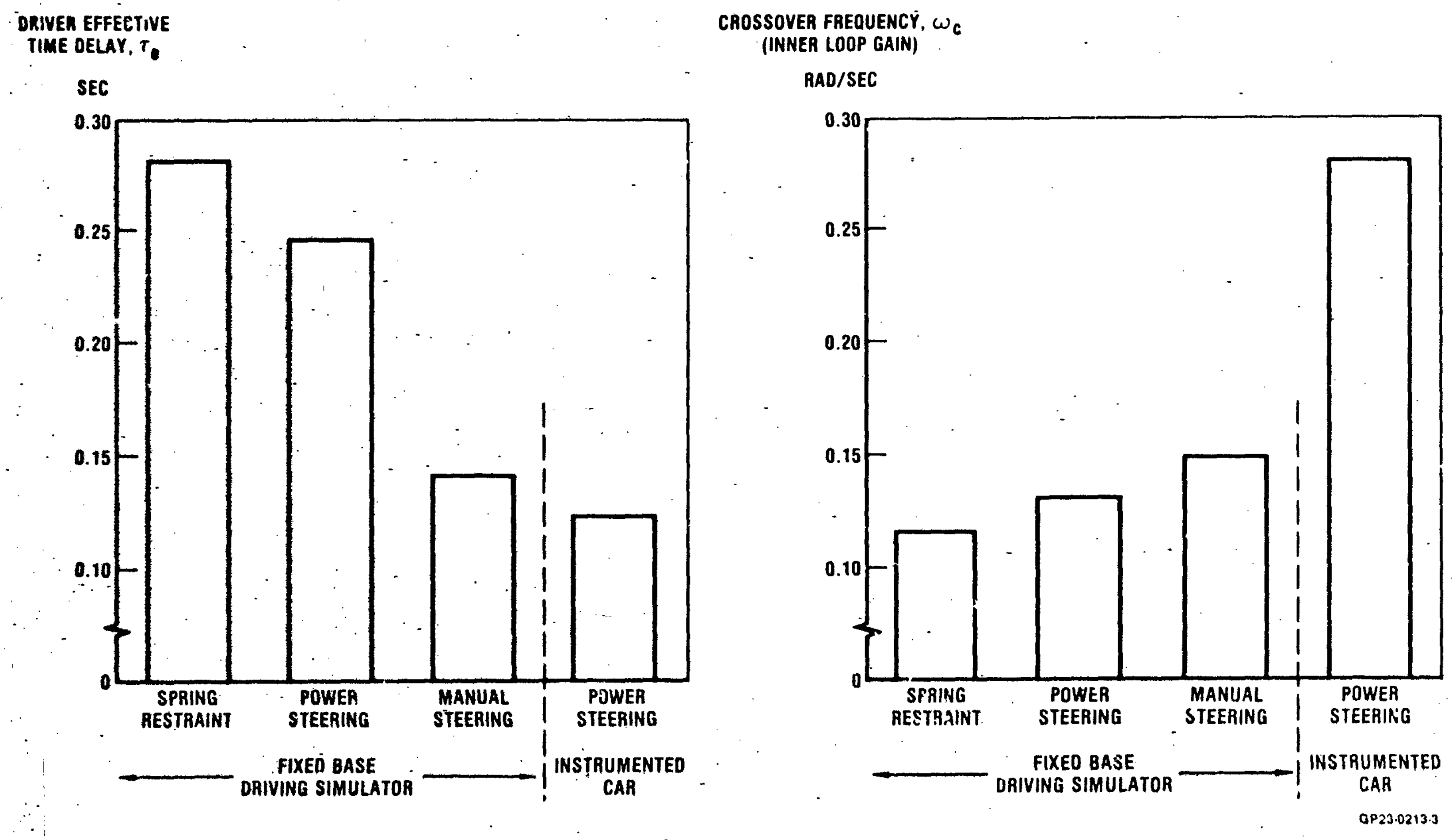


Figure 3. Effect of Steering Wheel Torque Feedback on Driver Effective Time Delay
Unpublished Data from STI Driving Research

a spring restrained manipulator. The kinesthetic feedback therefore consisted of all force, all position, and a blend of these, respectively. The effects on system performance and the human operator's describing function were obtained for three different sets of controlled element dynamics and two different forcing function bandwidths. It was generally found that the effective time delay of the human operator was lowest for the pressure or isometric manipulator. Performance was also best with the pressure manipulator, followed by the spring restrained manipulator, while the free-moving manipulator gave the poorest performance.

In Ref. 11, models were developed to explain the controller loading effects on the pilot's describing functions. The models in describing function measurements were analyzed to provide additional insight into the relative importance of kinesthetic cues of limb position and limb force in actuating the manipulator. It was found that the pilot generally uses good position feedback as a kinesthetic cue. Also it was found that when the inertia of the controller becomes a significant portion of the inertia of the total limb controller system, there are large performance degradations. In Ref. 12, Magdaleno and McRuer further explored the details of the neuromuscular system. This research provides direct describing function data for the coupled muscle manipulator actuation system. Data were obtained both for hand controllers and rudder pedals. The basic elements of the neuromuscular system involved in controller actuation are described for actual tracking situations using both isometric and isotonic manipulators. Isometric (or force controllers) are shown to give a higher actuation bandwidth because of the relatively rapid kinesthetic feedback allowed by the muscle spindles and golgi tendon organs. For isotonic (or free-moving) manipulators the actuation bandwidth was found to be much lower due primarily to the kinesthetic feedback of joint position which appears to have a significant time delay on the order of 0.09 seconds.

The basic model for the limb controller actuation system given in Ref. 12 is shown in Figure 4. Here we see a feedforward path representing the dynamics of the coupled muscle/manipulator system with feedbacks for both limb force and joint position. For isometric manipulators, the spindle feedback block operates essentially as a force feedback element with a high gain applied to the relatively small changes in manipulator position. For compliant controllers with large positional changes, the joint sensor feedback would play the primary role in determining the limb manipulator coupled dynamics. The dynamics for the feedforward muscle manipulator block can be illustrated with the mobility diagram as shown in Figure 5. Here we see that the muscle manipulator dynamics are derived primarily from mass of the limb, the controller compliance and damping due to the muscle, and compliance in the controller itself. Additionally, some compliance in attaching the muscle to the limb and some compliance at the pilot's grip with the controller also exist. This model can also be used to add additional forces as shown on the right side of Figure 5.

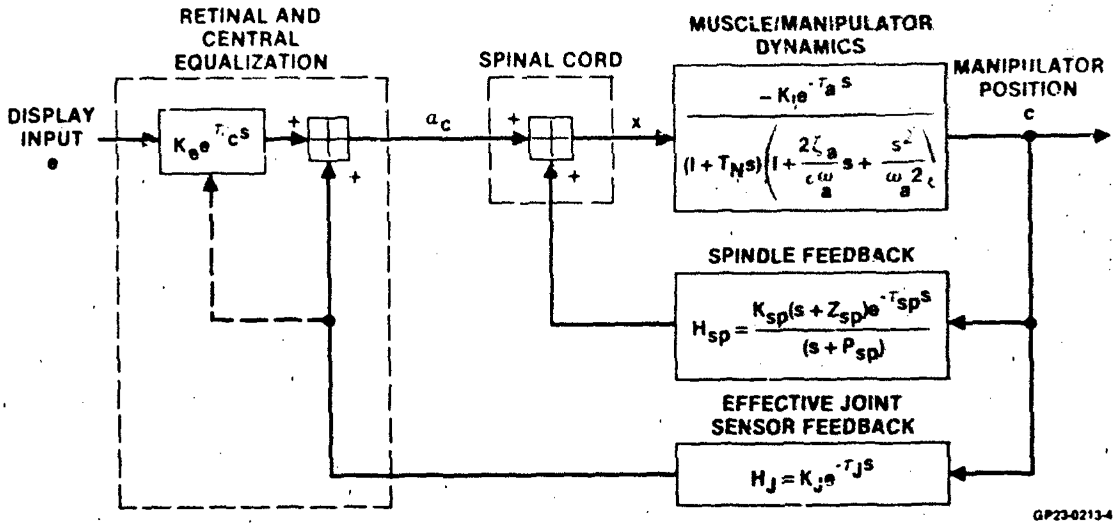


Figure 4. Neuromuscular Subsystems for Free-Moving and Isometric Controllers
Adapted from Reference 12

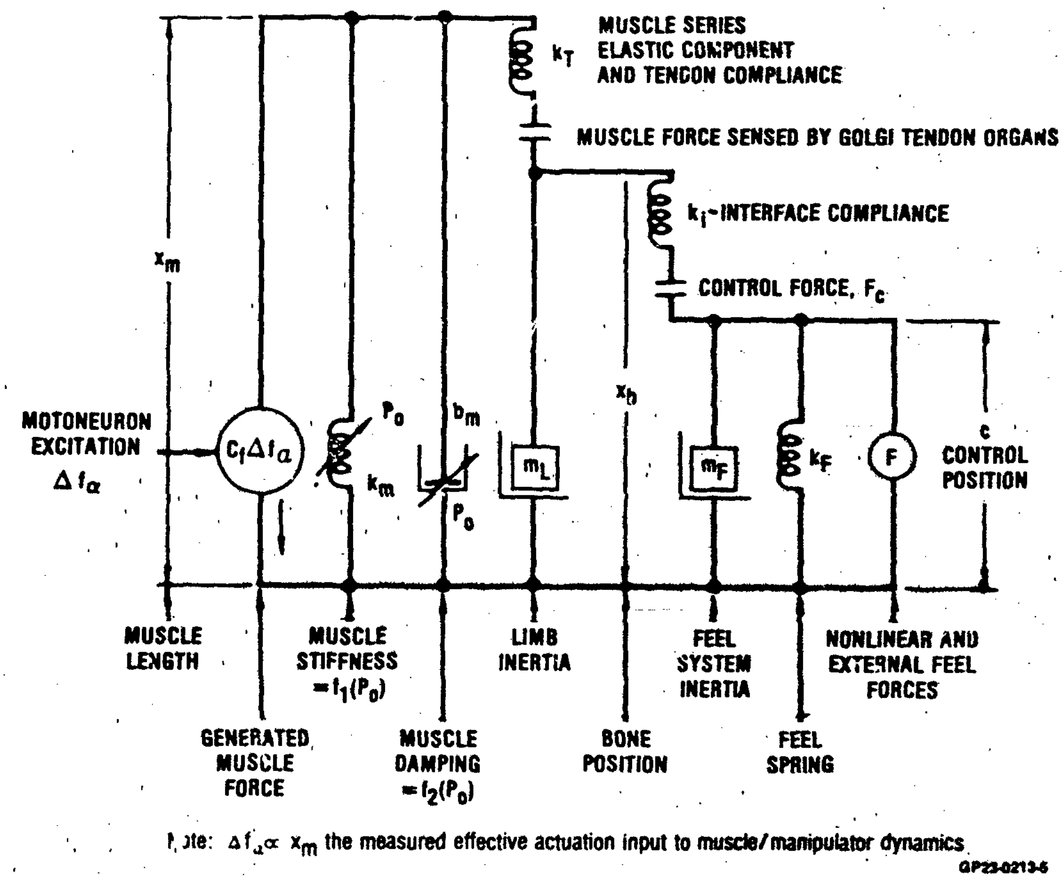


Figure 5. Simplified Mobility Diagram for Limb/Controller System
Adapted from Reference 12

The above detailed modeling work helps explain many of the tracking performance changes due to changing the loading properties and constraints of manipulators. For example, it potentially explains the superiority of pressure sticks over more compliant controllers. This modeling approach also allows us to describe what happens when inertial motions interfere with the pilots manipulation task. These effects are discussed in the article below.

4. EFFECTS OF MOTION FEEDTHROUGH AND DISTURBANCE - The majority of tracking research is done under fixed-base conditions where the human operator is free to perform without the potentially disturbing effects of motion. The basic processes by which vibration influences manual control system performance were investigated in Ref. 13. This study investigated the influence of vertical, lateral, and fore and aft sinusoidal vibration on manual control performance. Both describing functions and remnant measures were obtained in order to provide a thorough control systems analysis of the situation. As part of the study, body motions and controller response measurements were used. Biomechanical models were postulated to explain how vibration contributes to "control feedthrough." There were two primary effects of vibration on the human operator's describing function. First, the control motions were found to be dominated by the vibration in many cases. A large component of the controller output was directly correlated with the vibration. Second, the human operator's remnant or noise component (controller actions uncorrelated with either the tracking task input or motion environment) increased significantly under vibration conditions. The combination of the motion-correlated and disturbance components of the pilot's controller actions then caused large deteriorations in general tracking performance in the vibration environment.

In Ref. 13, a general process for the feedthrough of the motion environment into the control task was developed as illustrated in Figure 6. In this process, the human operator and controller are assumed to be mounted on the same structural platform which is driven by the motion environment. At low frequencies of less than 1/10 Hz, the operator and controller move in unison with the platform with no relative control motion. However, as frequency increases, the dynamic response properties or transmissibility of the human operator's body cause it to move at different amplitude and phase from the platform. The human operator's torso then undergoes differential motion with respect to the platform. Because the limb is attached to the moving torso, the torso motions are coupled through the limbs to the controller dynamics. This coupling induces vibration "feedthrough" to the human operator's controller actions.

Vibration feedthrough can also be caused by inertial forces that act directly on the mass of the arm and control stick. This situation arises in operational aircraft control situations. This "bobweight effect" will be discussed later. The coupling of the body transmissibility model to the dynamics of the limb-

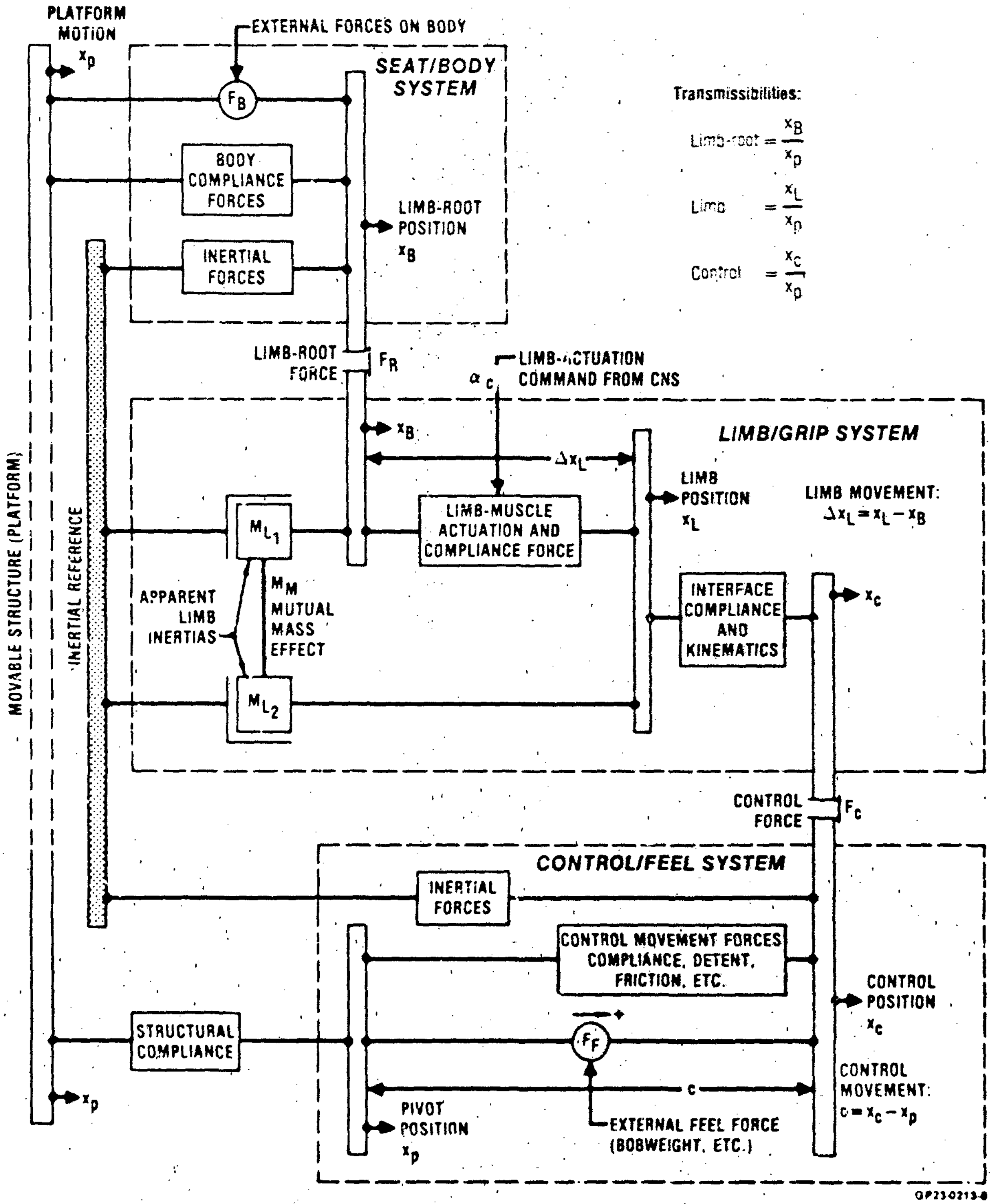


Figure 6. Limb/Controller Mobility Diagram Including Feedthrough Paths for Inertial Motions

control stick system result in the Fig. 6 model. Details of a biomechanical model for a given vibration axis and controller configuration can differ greatly, however. This project provides an opportunity to set up some simplified biomechanical configurations in which to analyze the results of various controller axis-task configurations.

Jex and Magdaleno (Ref. 14) have carried through a rather detailed biomechanical model for a semi-supine pilot operating a fore and aft moving controller. The basic configuration of this model is shown in Figure 7. Analysis has shown that this model can adequately describe measured vibration feedthrough to the hands and controller when the model is linearized about the appropriate configuration of display posture and controller. Some preliminary analysis is also described in Ref. 14 which relates to armrest effects which are typical of current sidestick controller configurations. Analysis in Ref. 13 also shows that fairly simple transfer functions can be used to explain the feedthrough effects for what may appear from Figure 7 to be a quite complicated biomechanical model.

5. <u>TRADITIONAL CONTROLLER FEEL CHARACTERISTICS</u> - Traditional mechanical electro-hydraulic feel systems in aircraft provide appreciable coupling with the pilot. The characteristics built into these "feel systems" are designed to provide significant kinesthetic feedback to the pilot to aid in his control task performance. Occasionally control problems are also introduced, however, because of the complexity of these feel systems. The first complete dynamic systems analysis of artificial feel systems was provided in Ref. 15. This report covered various artificial feel devices and components and provided design procedures and design criteria for including these elements in artificial feel system designs.

In a subsequent article, Potocki (Ref. 16) discusses the characteristics of aircraft feel systems from the pilot's point of view. In this article, he gives a good qualitative discussion of the various effects of feel system characteristics such as breakout, backlash, valve damping, etc. Potocki also introduces the concept of synthetic feel or stick steering systems wherein the servo system responds to an electronic signal from the stick and physical movement of the aerodynamic surface is fed back through a linkage to the pilot's controller.

In a later paper, Glenn (Ref. 17) discusses the functional characteristics of manual flight control systems. This paper reviews such factors as backlash, minimum increment of control, position lag, surface velocity limits, etc. Each of the detailed functional characteristics of typical manual control systems are discussed and the complex inter-relationships among them are considered. Some pitfalls and problems to be avoided in design synthesis are included.

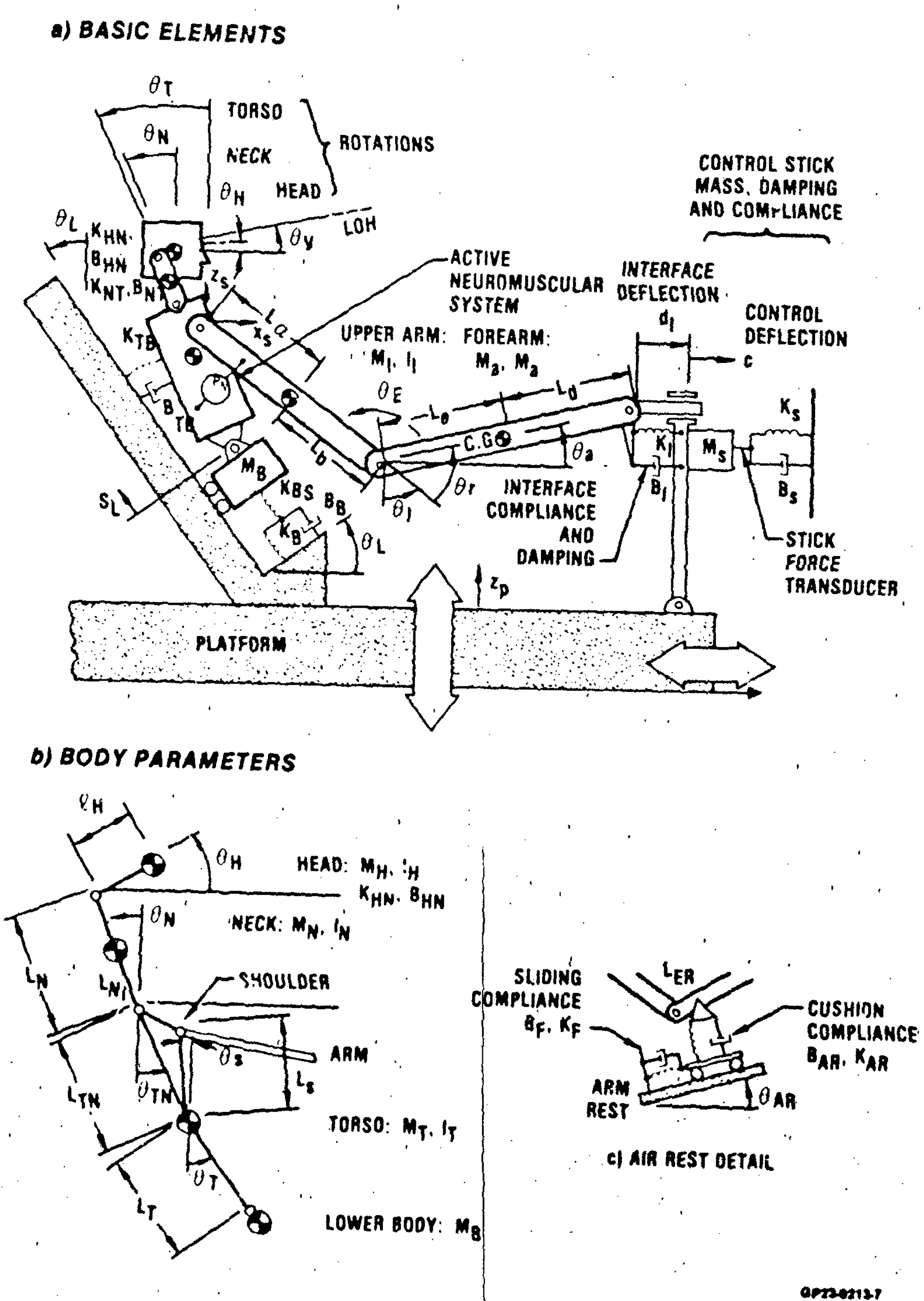


Figure 7. Biomechanical Model for Pilot Pitch Axis Control

Over the years a variety of stability problems have arisen with mechanical flight control system elements. McRuer and Johnston (Ref. 18) reviewed these various linear and nonlinear control system characteristics which can lead to stability problems. In terms of linear characteristics the problems associated with large inertia (heavy bobweights) and low feel spring gradients lead to control system lags and thus reduced damping in the mechanical control system. The effects of friction and backlash which are often troublesome nonlinearities are also discussed in some detail.

Many of the stability problems associated with mechanical feel systems can be avoided by fly-by-wire systems, and, in fact, this is one rationale for going to fly-by-wire systems. This matter is discussed further in the following article.

6. <u>SIDESTICKS AND FLY-BY-WIRE SYSTEMS</u> - In modern aircraft design there is a strong tendency at the design stage to go with fly-by-wire systems and also with sidestick controllers. Bumby (Ref. 19) analyzed fly-by-wire systems coupled with the control configured vehicle concept and shows that potential weight reductions are possible. Some of the advantage derives from neutral vehicle stability design which is allowed by the inherent SAS function of fly-by-wire flight control systems. In describing the F-16 system, Livingston (Ref. 20) claims further advantages of fly-by-wire systems. These include reduced weight and volume, increased system survivability due to redundancy and other factors, and improved maintainability. These characteristics combine to make fly-by-wire systems very attractive to the designer and can lead to additional benefits in controller design such as side-mounted sticks.

Side-mounted sticks received early enthusiastic support by test pilots. In one report (Ref. 21), an experimental sidestick installation in an F-104D was discussed. Aircraft control with the sidestick was described to be positive and somewhat more precise than the standard centerstick. The sidestick allowed the achievement of equal or superior trajectory control in various maneuvers with a drastic reduction in pilot workload. The handling qualities of the sidestick, especially its lighter force gradient, proved it to be superior to centerstick control. The experimental installation also never experienced any component failures and had a perfect reliability record. The sidestick led to improved comfort and body stability. Finally, the sidestick installation would allow for a significant increase in forward cockpit console area which could be used for weapon switches and communications navigation displays. More space was made available on the front console than was lost on the right side console.

Reference 21 gives some specific human factors guidelines for the anthropometric arrangement of the control axes and neutral stick position. Also, specific guidance is given for stick-mounted switches. The switches must be one inch or less above the forefinger. It is also recommended that the pilot be able to sense physical movement in order to know when the switch is being activated. Furthermore, it is suggested that the actuation forces for the switch be at least 50 percent below the breakout forces of the main hand controller in order to avoid spurious inputs to the control stick. The experimental sidestick installation in Ref. 21 allowed for a damping-to-stick motion which was variable. Apparently, this feature was perceived to be useful to control the dynamic response of the controller and yet not affect the steady state stick forces. A majority of the pilots in the Ref. 21 study reported a major decrease in pilot workload when using the sidestick as opposed to the centerstick. It was concluded that pilots preferred the sidestick to the centerstick.

Klein and Hollister (Ref. 22) describe an F-16 CCV experiment involving a fixed-base simulation. An isometric F-16 sidestick was used with an isometric thumbstick to control the CCV direct force modes. A landing task was simulated, and novel display formats were tested that would show the direction and magnitude of the vehicles inertial acceleration (similar to Bernotat's display format (c) in Ref. 6). It was found that the direct force CCV mode allowed a 30 to 40 percent improvement in approach tracking ability in the face of wind gusts. With the addition of the new display concept an additional improvement of 10 to 15 percent was realized. This result shows the importance of considering the interaction of display format with CCV modes. From the experience gained in this study it was also felt that thumb control of the direct force modes allowed better control of the magnitude of the CCV input than of the appropriate direction of control. The inability to control the direction of inputs would presumably lead to cross axis control. The utility of the novel display format was felt to be due to the indication of the CCV input direction which was provided as a displayed feedback to the pilot. Reference 22 appears to be the first study which has focused some detailed attention to the coordination between the thumb control switch and the hand controller. The effects described could be easily assessed with describing function measurements in the various control axes in combination with suitably designed command and disturbance forcing function inputs.

Sidestick spring gradients and control sensitivity are an important issue. Myers, et al, (Ref. 23) have compared the sensitivity characteristics of various sidestick controller applications including the Space Shuttle Orbiter, the F-16 fighter and the Calspan NT-33 experimental sidestick installation. The controller sensitivity characteristics are compared and summarized in Fig. 8 on the basis of torque applied to the sidestick handgrip for the roll control axis. In the top half of Figure 8, note that both the Space Shuttle and F-16 require higher torques for a given roll rate response than the various gain conditions tested in the NT-33. The lower vehicle response sensitivity for these two vehicles probably represents concern for minimizing the possibility of over-control. In the lower half of Figure 8, the force-deflection characteristics of the various controller

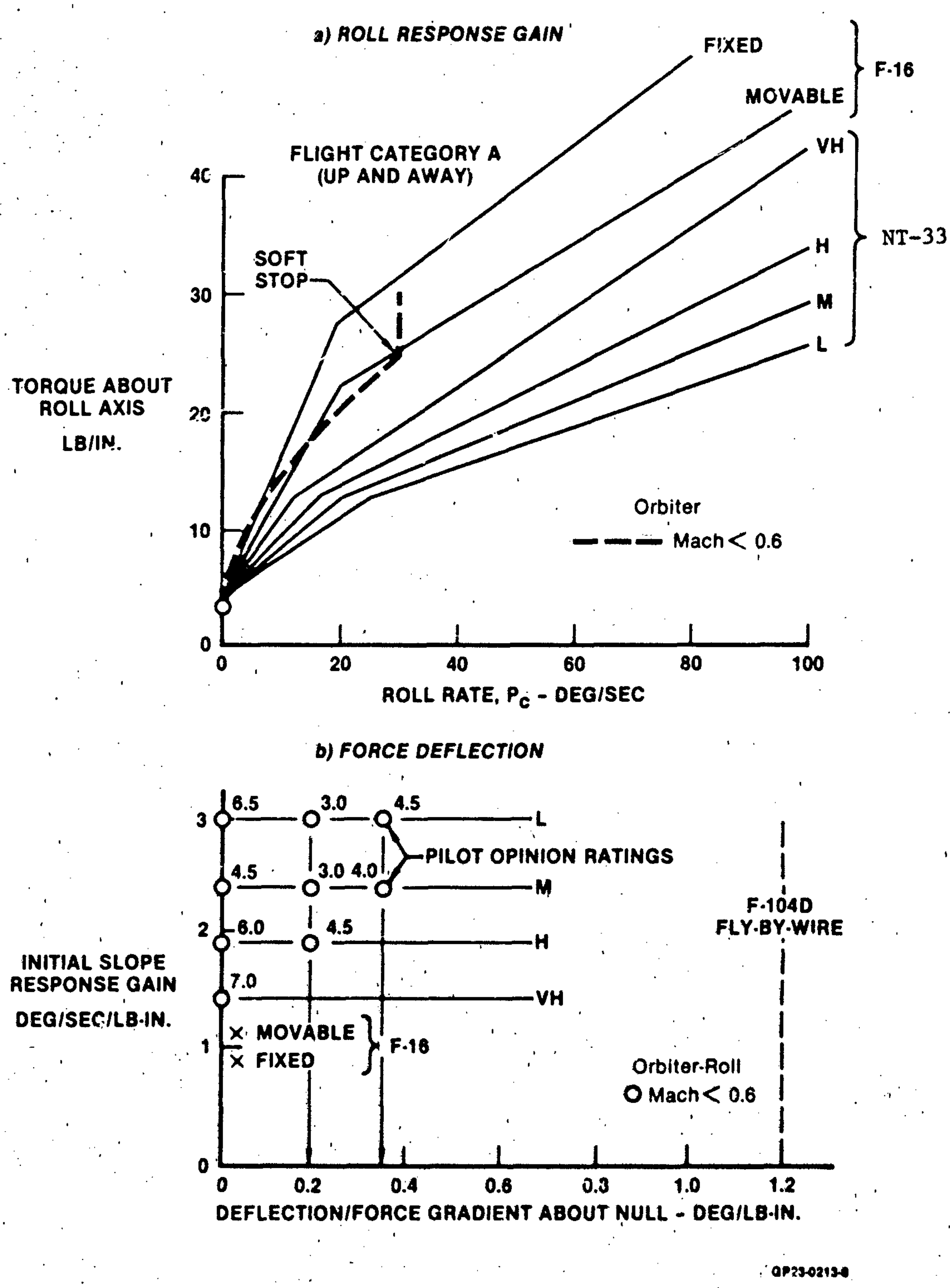


Figure 8. Summary of Operational and Research Data on Controller Gains and Force/Deflection Characteristics
Adapted from Reference 23

installations are illustrated. Note that the F-16 represents a very stiff stick even in the current "moveable" configuration that was developed after initial flight tests showed a PIO tendency. Pilot opinion ratings for the NT-33 test showed that ratings improved as some deflection is allowed in the sidestick. The Space Shuttle deflection characteristic is much larger as noted in the bottom of Figure 8. Also noted in the bottom of Figure 8 are the force-deflection characteristics of the F-104D installation described in Ref. 12. The roll rate response for these deflection characteristics was not given in Ref. 21 so it is not noted in Figure 8. We can see that the force-deflection characteristics in Figure 8 span a wide range. A factor of almost 60 to 1 exists between the F-16 characteristics, which are still considered too stiff, to the orbiter and F-104D characteristics which are considered by Staten to be too flexible.

There are two inferences to be drawn from the bottom half of Figure 8. One is that the force-deflection characteristics probably have a very broad range of acceptable characteristics. Also, further research is required over a broad range in order to better define the appropriate force-deflection characteristics for a sidestick installation. Future research must consider the effect of inertial forces acting directly on the mass of the arm and control stick. Additionally, the effect of using additional controllers mounted on the sidestick, such as a thumb isometric for controlling CCV modes, must be investigated. These devices may require some compromise in the basic controller force-deflection characteristics.

7. MODELING AND ANALYSIS - Structural and parametric models for CCV mode control in various task situations will be very useful in the definition and mechanization of simulation task inputs and measurements and in the analysis of the subsequent results. A basic review of general pilot models is given by McRuer and Krendel in Ref. 24. Included are detailed structural models for the pilot, including remnant effects and general treatment of multi-loop manual control systems. As discussed previously, models for limb manipulator interaction are given in Refs. 10 and 12, and biomechanical models which allow for the direct control influence of motion environment on controller actions are given in Refs. 13 and 14.

Jex, et al, (Ref. 25) describe models for the human operator in a motion environment that will be of direct importance in the motion-base simulation to be carried out on the second phase of this project. The models in Ref. 25 account for the influence of translational acceleration and angular rate. Results indicated that rotary motion cues are used primarily in the role of stability augmentors, i.e., as rate dampers, and that lateral specific force cues below 1/10 g are ignored or have small effects. From the simulator fidelity point of view, some results indicate that grossly spurious motion distortions due to washout filter dynamics were rated worse than no motion at all. Optimum combinations of attentuating and first order washout filtering were found for the roll motion drive logic. Also, an adaptive nonlinear logic was developed and validated for sway drive logic.

Hoh, et al (Ref. 26) provide a rather comprehensive analysis of handling quality criteria for CCV aircraft control. It was found that the unconventional response mode controller requires additional manipulators to be controlled. Therefore, it can generally be criticized as offering slower response and lower authority in addition to increased workload. One exception is the flat turn mode in a dive bombing task. The maneuver enhancement mode was found to be of positive benefit across the board, however, because of potentially faster responses from the conventional controller. The exploration of equivalent enhancement mode for lateral-directional responses from the conventional controller. It is shown that as a practical matter, it is difficult to achieve a pure CCV mode because of various cross-coupling and crossfeed effects. Some modes such as the translation modes are particularly sensitive to this problem. Reference 26 discusses several pilot loop closures for the combination of different flying tasks and different CCV modes. The block diagram structure of the resultant models will be quite useful in planning simulation experiments for this effort.

8. SIMULATION AND IN-FLIGHT EXPERIENCE - In this section we will examine those reports describing simulation of, or in-flight experience with, uncoupled control modes.

a. Spacecraft And Large Aircraft - Wittler (Ref. 27) describes the evolution of spacecraft hand controllers from the basic mechanical linkage used in the Mercury spacecraft to the total fly-by-wire three-axis device used to control the Apollo spacecraft. Due to environmental and crew station integration problems, it was determined early in the Mercury project that the floor mounted "rudder" pedal could not be used for yaw control. This restriction led to the development of a three axis hand controller in which yaw was controlled by twisting the hand grip about the vertical axis. This control scheme was utilized throughout the manned space effort. Figure 9 illustrates the direction and range of motion used in the Apollo hand controller.

Vertical and lateral translation and acceleration have been examined as a landing approach aid for transport aircraft. Chase, et al (Ref. 28) performed a motion-base simulation of several types of Direct Lift Control (DLC) applied to the C-5A aircraft. DLC in this case is a vertical acceleration control generated by augmenting conventional elevator input with flap deflections. Two of the configurations were of the Maneuver Enhancement (ME) type, i.e., DLC was used to increase the normal acceleration response of the aircraft to conventional stick inputs. The third configuration used a collective pitch type lever to allow the pilot to control flap deflection independent of elevator inputs. Evaluation pilots endorsed the use of ME in all missions investigated. The separate DLC resulted in a degradation of pilot rating due mainly to the controller and mechanization used. The simulator was a modified Link T-37 motion-base simulator. Evaluation tasks included landing, terrain following, and general handling qualities evaluation.

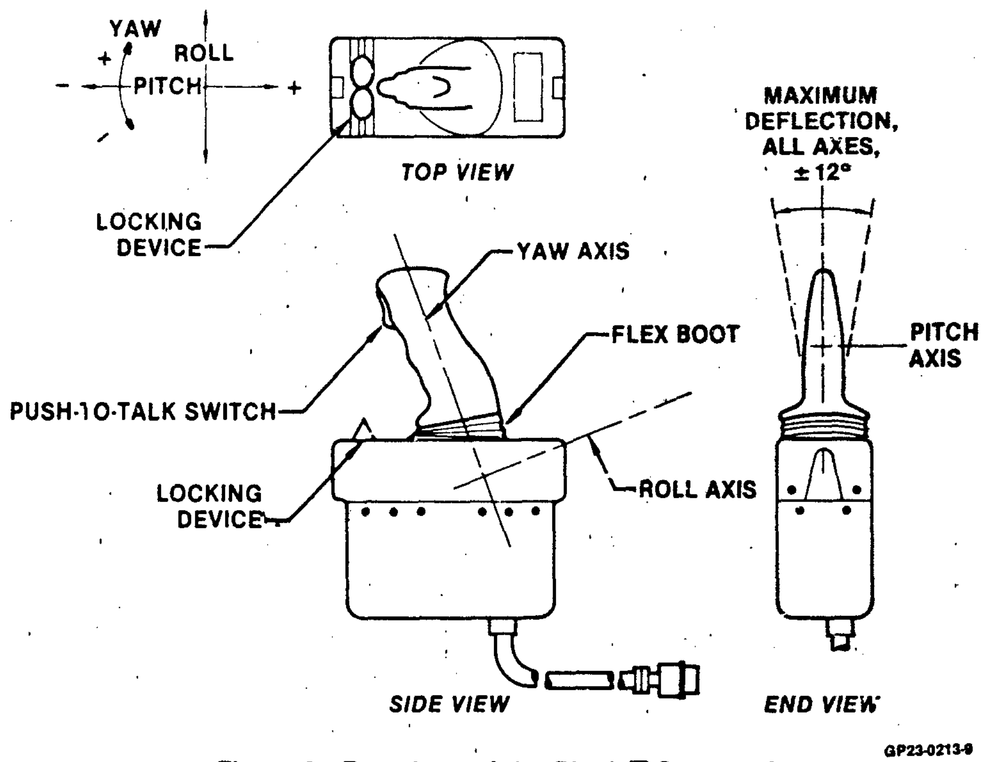


Figure 9. Functions of the Block II Command Module Rotational Hand Controller
Adapted from NASA TN D-7884

Barnes, et al (Ref. 29) describe a fixed-base simulation of the Vickers Super VC10 transport augmented with a combination blended DLC and "maneuver boost" (a transient elevator input to speed pitch response). While blended DLC did indicate some improvement to the landing task, the combination of DLC and "maneuver boost" yielded the best performance.

References 30, 31 and 32 describe the use of decoupled controls in the landing of a large STOL transport. These fixed- and motion-based simulations utilized an interesting combination of controllers. A column-mounted control wheel, rudder pedals and throttle were used to investigate the following: flight path controlled by column inputs, pitch angle with the flap lever, velocity with the throttles, yaw rate with the control wheel, and sideslip angle (lateral-translation velocity) with the rudder pedals. A thumbwheel on the left yoke horn was used to trim flight path angle and a thumbwheel on the right horn to trim sideslip angle. In general, pilot ratings were excellent.

Feinreich, et al (Ref. 33) describe the use of decoupled conventional longitudinal controls for the approach and landing of a STOL aircraft as simulated on the Princeton Navion in-flight simulator. A yoke, column and throttle were used. Control assignments were: column to control flight path angle with trim capability supplied by button on the left horn, throttle to control forward speed, and a pitch thumbwheel to control pitch attitude. The decoupled controls tested were found to have good flying alities and resulted in small touchdown point dispersion with low sink ratio.

In an investigation of Direct Side-Force Control (lateral translation velocity) for STOL crosswind landings, Boothe and Ledder (Ref. 34) utilized the capabilities of the CALSPAN Total-In-Flight Simulator (TIFS). The pilot was given manual control of lateral velocity with a thumbwheel mounted on the right control yoke horn or the first throttle lever depending on pilot preference. Since normal landing procedures call for one hand on the throttle at all times, the majority of pilots used the throttle mounted thumbwheel. Another interesting configuration was the use of an automatic system using the ILS localizer signal to compensate for crosswinds, thus leaving the pilot with only the longitudinal control task. This greatly reduced pilot workload. However, mechanization difficulties resulted in objectionable lateral acceleration oscillations. In all cases pilot comments were favorable in canceling crosswind effects up to 15 Kts, the design limit of the system.

Mooij, et al (Ref 35) performed a literature survey of blended Direct Lift Control as applied to transport aircraft. They discuss the only active aircraft with DLC along with various simulation and flight test experiments. The following conclusions were formulated.

- The concept of direct-lift control shows great potential for the improvement of the controllability during final approach and landing of large transport aircraft.

- The advantages obtainable by using direct-lift control to provide short term (high-frequency) lift modulation combined with the use of the tail surfaces for long term control, hold equally well for manual as for automatic control.

- Maneuver enhancement through direct-lift control should not lead to a degradation of the quality of pitch control; direct-lift control shall therefore preferably be used in conjunction with a command and stability augmentation system.

The report goes on to describe a simulation conducted at NLR to aid in the determination of low-speed longitudinal criteria for transport aircraft. One of the criteria which was developed is for minimal required maneuver enhancement with blended direct-lift control.

b. <u>Fighter Aircraft</u> - Several references have been identified in which the advantages of uncoupled motion capability for fighter aircraft have been reported. Mooij (Ref. 36) investigated the use of Direct-Lift Control (vertical translation acceleration) as a carrier landing approach aid on Navy aircraft. The configuration was tested on the Princeton variable-stability Navion aircraft. Three controllers were examined in this study. The centerstick was used in the investigation of a maneuver enhancement mode in which DLC was blended with conventional moment control to increase altitude response. A spring-loaded, three-position stick-mounted switch was installed to investigate the use of step-up or down DLC inputs (bang-bang control). The use of a center-loaded thumbwheel for proportional control of vertical translation was also examined. The latter two controllers provided altitude control with little or no change in pitch attitude. A wide range of simulated aircraft dynamics was examined. The task was a simulated carrier approach using a visual "meatball" glide slope indicator. All implementations resulted in improved pilot ratings ranging from small to large differences when compared with conventional moment control. The pilots preferred the proportional control but tended to use it in a bang-bang type control strategy. The preference for the proportional over the bang-bang controller is thought to be due to the "adverse" pitch rate disturbance caused by the latter's high flap deflection rate.

Miller and Traskos (Ref. 37) conducted a brief evaluation of proportional vertical translation control with a stick-mounted thumbwheel as part of their Navion simulation of approach and landing. These configurations operated on the "backside" of the power required curve, i.e., throttle was used to control sink rate while pitch controls airspeed. Pilot rating and comments indicated improvements in approach due to vertical acceleration control, especially in the low short-period frequency configurations. The use of proportional control reduced the need for making power corrections in the close-in part of the approach. This is particularly beneficial for configurations having poor throttle response characteristics.

The incorporation of Direct Lift Control (vertical translation acceleration) on the F-8C aircraft was investigated on groundbased simulation and flight test evaluations in Ref. 38. This system utilized the existing ailerons drooped as a variable flap. The pilots' DLC control knob was located on the grip and provided either bang-bang or proportional control depending on pilot selection. In a fixed-base simulation, four pilots endorsed the use of DLC because of improved glide path control. Statistical analysis of the simulated approaches indicated a reduction in touchdown dispersion due to DLC. Flight tests on the actual aircraft confirmed the simulator findings. Glide path corrections near touchdown were made with DLC that could not be done with conventional moment control. The combination of DLC and an auto-throttle were found to greatly reduce pilot workload in landing.

The aircraft of Ref. 38 was released to the Naval Air Test Center (NATC) for further evaluation (Ref. 39). DLC was found to significantly increase the pilot's ability to control glide slope, reduce touchdown dispersion, and reduce average sink speed. Reductions in recommended approach speed appeared achievable with DLC due to the increase in glide slope control available. Recommendations included the incorporation of the system on all fleet F-8 aircraft and investigation of the feasibility of DLC incorporation in current and future jet carrier based airplanes.

Chase, et al (Ref. 28) investigated the incorporation of DLC (again a vertical acceleration control) on the F-104 aircraft. The control schemes were as used on the C-5A experiment reported earlier, with appropriate changes in authorities and rates for the fighter aircraft. The pilots indicated the desirability of the maneuver enhancement type control systems for the simulated tasks of landing, terrain following and inflight refueling. The separate DLC input with a flap handle was not liked due to the controller and mechanization used.

Hall (Ref. 40) describes the implementation and evaluation of direct side-force control on the variable stability NT-33 aircraft. Drag petals on the wing tips combined with rudder deflections were used to provide Lateral Translation (LT) or Wings Level Turn (WLT) capability. Controllers included centerstick with roll stabilization, stick-mounted thumbwheel, or the rudder pedals. Figure 10 illustrates the thumbwheel position on the stick grip. The pilot was provided with a sideslip indicator and sideslip angle in degrees. The evaluation pilots noted several airplane and control system limitations during configuration evaluation in a dive bombing task. These were:

1. A maximum steady yaw rate of 0.5 deg/sec or the equivalent to approximately an 8° banked turn at 240 knots IAS at 15,000 feet or approximately 9 mils/sec.

2. A maximum steady sideslip of 3.5 deg or approximately 31 feet per second side velocity at 240 knots IAS (503 ft/sec) at 15,000 feet.

3. The lack of a spring type centering device on the stick mounted thumb controller.

4. The shallow speed-stabilized dive angle limit of 25°.

5. The lack of a gunsight.

6. The short duration of the evaluation flights (1.4 hours).

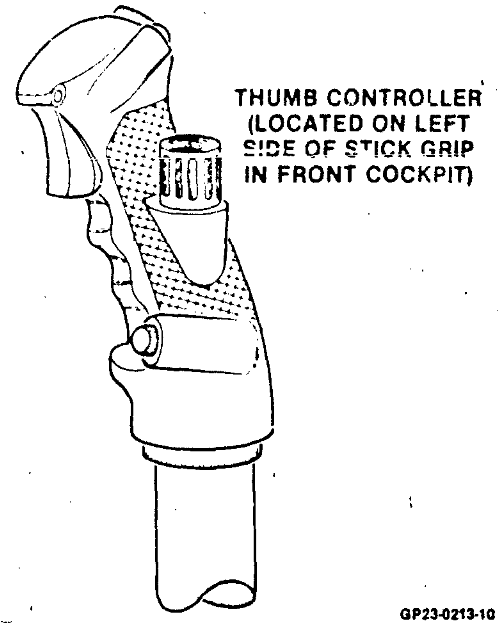


Figure 10. Side Force Controller from Reference 40

The evaluation task was a 25°, 240 kt speed-stabilized dive bombing run with roll-in occurring 7000 to 9000 feet above ground level and pull-out initiated 1000 to 2000 feet above ground level. Based on pilot ratings and comments the following conclusions were drawn regarding uncoupled motion and the controllers used:

1. All of the evaluation pilots felt that the direct side-force control system, as mechanized to control steady yaw rate, provided a significant improvement in their ability to acquire and maintain a target over that achievable with the basic T-33 airplane. Not all of this improvement, however, can be attributed to direct side-force control, since part comes from the stabilization provided.

2. The ability to make one correction for a lateral target displacement using direct side-force control was considered a significant improvement over having to make two bank angle corrections to get the same result.

3. The use of direct side-force to command a steady sideslip (lateral translation) does not present a practical method of controlling lateral aim point for weapons delivery but may be useful for station keeping, inflight refueling or as a crosswind landing aid.

4. Direct side-force control (wings level turn) holds promise as a method of improving weapons delivery accuracy and general flight path control; therefore it should be investigated further.

5. Careful attention must be paid in designing a direct side-force control system to minimize pitching and rolling moments that may result from the deflection of aerodynamic surfaces used to generate the side-force.

6. The nonlinear rolling moments associated with the variable stability T-33 direct side-force mechanization were less degrading than the pitching moments Nonlinear function generators were required in the aileron and elevator channels to eliminate these unwanted moments. With the function generators included, none of the evaluation pilots reported detecting any nonlinearities in the system or airplane characteristics peculiar to the side-force mechanization.

7. Consideration of an independent side-force controller other than one of the primary flight controllers is worthwhile and should be further investigated.

8. The thumb controller mechanized in the T-33 was not considered a satisfactory direct side-force controller.

9. The lateral stick was acceptable as a direct side-force controller, but it lacked the flexibility that was available with the thumb controller or rudder pedals since roll stabilization was always a requirement. The "unnaturalness" of using the lateral stick for directional control reduced its desirability.

10. If a primary flight controller is to be used as a direct side-force controller, the rudder pedal mechanization is superior to the lateral stick.

11. The heavy side-force controller forces first evaluated using the lateral stick (4.5 lb per inch) and rudder pedal (130 lb per inch) were unsatisfactory. The reduced values of 3.0 lb per inch and 80 lb per inch, respectively, were considered satisfactory. Care must be exercised when designing a side-force controller to achieve the proper sensitivities to allow rapid corrections to be made and still maintain sufficiently fine control to hold the pipper on target without over-controlling.

12. Additional evaluations should be performed to determine the desirability or difficulties of direct side-force control as a function of Dutch roll damping ratio and other important handling qualities parameters.

Hall (Ref. 41) again used the direct side force capability of the variable stability NT-33 in an evaluation of the Wings Level Turn (WLT) capability of the Northrop A-9A tactical attack aircraft proposed for the AX competition. Tasks were a 25°, 250 KIAS dive-bombing maneuver commencing at 4,000 to 6,000 feet above ground level, with recovery no lower than 1500 feet, and a 15° 225 KIAS strafing maneuver initiated at 2500 - 3000 feet with recovery no lower than 400 feet. WLT authorities were similar to those of Reference 40 and commanded through the rudder pedals. The Northrop configurations included a 40 mil/g sideslip lead. Controller parameters varied during the evaluation were rudder pedal gradient, hysteresis and breakout forces. For the 15° dive there was very little change in pilot rating for changes in rudder pedal force gradients or breakout force hysteresis combinations. For the 25° dive configurations, increasing the force gradient degraded the pilot ratings. The same trend was noted for an increase in rudder pedal friction. The gradients and friction effects tested will be examined in more detail later in this report. The reference does include a thorough review of evaluation methods. It should be mentioned that large pitching moments due to use of a split flap device to generate the required yaw on the actual A-9 combined with cost constraints, resulted in deletion of the effort.

Carlson (Ref. 42) examined the advantages of direct side-force control in dive bombing. Experiments were carried out on the NASA FSAA motion-base and the Boeing MSS fixed-base simulators. The side-force capability was added to the basic F-8 flight control system by the addition of two vertical canards near the aircraft nose. The aerodynamic characteristics of these surfaces were predicted analytically. The pilot had control of four aircraft maneuvering modes, two of which were uncoupled. A third was a form of lateral maneuver enhancement and the fourth provided coordinated conventional bank to turn. Each was available at all times and was commanded by a separate means of control. These were:

- Wings Level Turn - commanded by rudder pedals
- Lateral Translation - commanded by throttle-mounted thumb controller (Figure 11)
- Lateral Maneuver Enhancement - commanded by simultaneous deflection of lateral stick and appropriate rudder pedal
- Coordinated turn - commanded by lateral stick deflection.

The task was a 30°, 556 kt. dive bombing maneuver initiated at 8000 feet with bomb release occurring at 3000 feet above ground level. Results were compared to scores generated by flying the same mission with the conventional F-8 maneuvering capabilities. Crosswinds were added to increase task severity. However, due to display limitations (approximately $\pm 20°$ vertical viewing angle) a

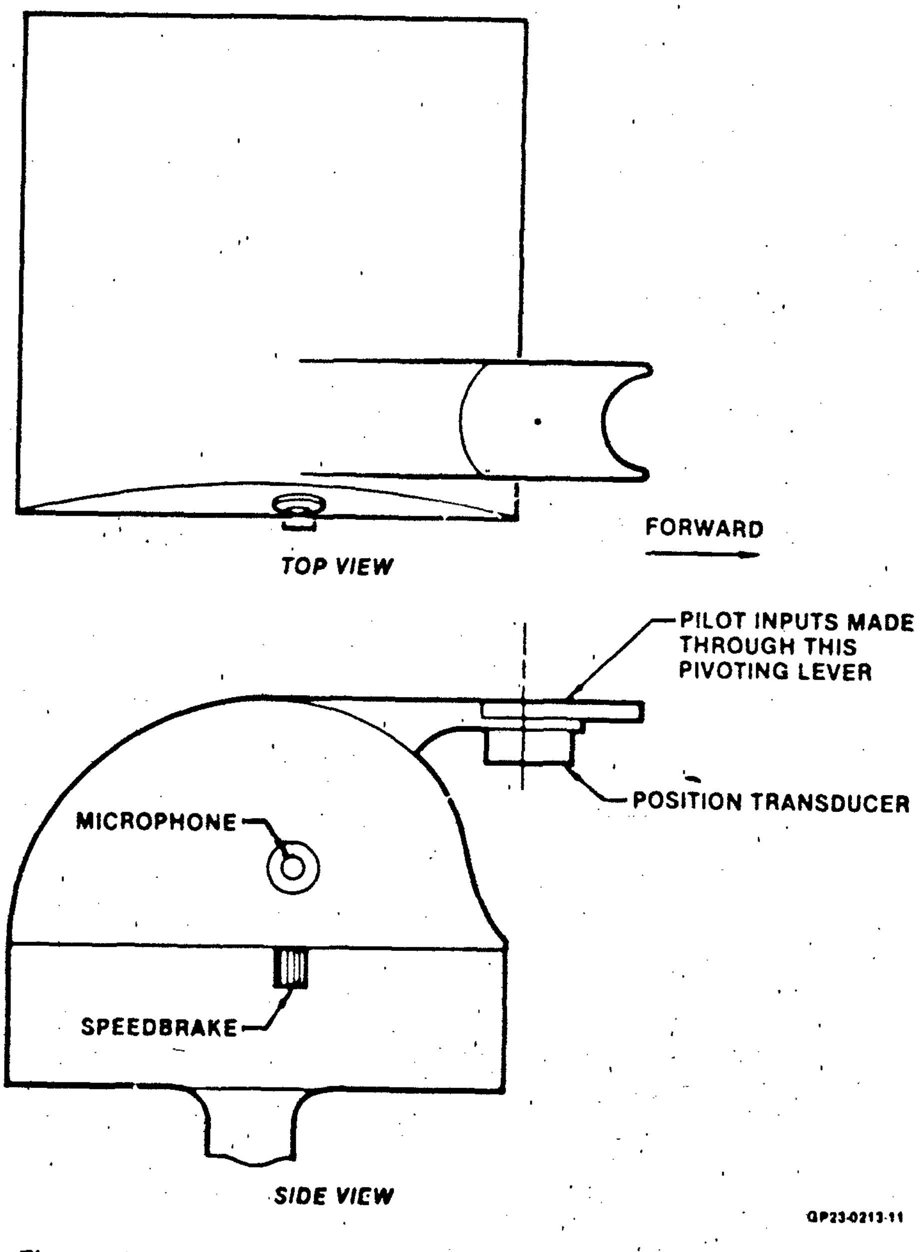


Figure 11. Throttle Mounted Side Force Controller from Reference 42

roll-in maneuver was not executed. The bombing runs were started at a point where it was assumed that the pilot had just rolled out in a 30 degree dive angle. Various lateral offsets to the target were used. It was found that scores improved with larger offsets. This was later traced to a "boredom factor" due to the simplicity of the tasks. One of the pilots admitted to trying harder as the task got more difficult. This "boredom factor" was indicated by the data to have affected the test results of all the pilots. Future efforts should attempt to avoid this problem by developing more demanding tasks. A crosswind landing task was also evaluated during the simulation. Lateral translation was used to cancel the effect of the crosswind, but its low authority and slowness of response limited its usefulness. Concerning the direct side-force control (DSFC), the following conclusions were drawn:

1. The use of DSFC for weapon delivery was shown to improve accuracy by a factor of 3 over conventional control.

2. Pilots who flew the simulation felt there would be no problem with lateral accelerations up to 1 g.

3. Pilots who flew the simulation stated that the use of DSFC significantly reduced pilot workload by providing simpler, more precise control.

4. DSFC increased aircraft maneuverability significantly. Heading changes less than 10° could be achieved twice as fast using WLT in place of conventional control.

5. Authority limits between .6 and 1.0 g are adequate for dive bombing.

6. DSFC reduced pilot workload for crosswind landings, however, authority would have to be increased by a factor of 3 to handle a 15 knot crosswind.

The report concludes with a recommendation for installing and flight testing the system on an F-8.

Hove, et al (Ref. 43) describe fixed-base simulation of an advanced technology close air support aircraft configuration known as Lightweight Attack Configuration 29 (LWA 29). This design concept employed powered lift in the form of vectored thrust with supercirculation (VT/SC) and direct side-force control (DSFC). The VT/SC used vectored thrust from a wing duct containing additional burners. The evaluation task was a dive-bombing maneuver in which the thrust was vectored at roll-in and power was added at pull-out to get the desired quickening of the normal acceleration. Dive angles of 30°, 45° and 60° were examined. The basic advantage of the system over conventional control was to reduce the altitude loss in the pullout, and to reduce the time to climb to altitude. Both results were considered beneficial in that low altitude exposure of the aircraft was reduced and survivability increased. In landing, the use of VT/SC considerably reduced approach angle of attack, thereby greatly improving pilot visibility.

DSFC was evaluated in a separate simulation independent of the VT/SC system. Two types of direct side-force were examined, lateral translation and wings level turn. In addition two types of controller for the DSFC were evaluated, namely rudder pedal control and an isometric button mounted on the isometric side-stick controller. The task was ground attack using conventional bombs and a fixed depressed reticle sighting system. Each run started with a 12,000 ft range and a 12,000 ft lateral offset from the target and included a roll-in from an initial altitude of 13,000 ft at 400 KIAS. Dive angle was 45° with a release altitude of 4000 ft at 558 KIAS. Azimuth errors for all configurations (conventional and DSFC) and controllers (rudder pedal and button) were small with the uncoupled modes exhibiting little or no improvement in azimuth accuracy. Two possible reasons for this were examined. (1) The maneuver allowed 10 to 15 seconds for fine tracking, which was adequate to achieve accuracy using conventional control. (2) Pilot inexperience with uncoupled aircraft motion. The simulation allowed little time for the evaluation pilots to familiarize themselves with the capabilities of the uncoupled modes. A significant reduction in elevation errors was noted for DSFC commanded by the thumb switch. The lack of improvement with rudder pedal control was linked to the separation of function: elevation by hand and azimuth by foot. This was believed contrary to normal procedure of hand control for both axis. Based on total miss distance, wings level turn controlled by the thumb button appeared superior to other means of control. However, pilot comments indicate a concern over coupling into the normal control stick on which the thumb button is mounted. In evaluation of the same combinations in crosswind landings, the thumb button commanding the lateral translation (LT) mode was found to be smoother than any other control mode. Lateral translation using the rudder pedals was the next best control mode.

Another simulation investigated the survivability of the LWA 29 in the presence of an anti-aircraft artillery (AAA) threat. The evaluation included man-in-the-loop simulation of an advanced radar-controlled, 23 millimeter gun using a quadratic radar prediction algorithm in order to simulate a more advanced fire-control system than the linear prediction methods then used. For the AAA, the probability of kills (P_K) against a non-maneuvering target was almost 1.0 (perfect). Against an S-weaving target the P_K was reduced by a factor of one third. A target velocity of 400 kts produced lower P_K's than a 600 Kt target because of the greater amplitude of motion by the target due to lower turn radii at the lower speed. Jinking by the target reduced the P_K's to zero regardless of the use of VT/SC and DSFC. When the target attacked the AAA site, the initial roll-in to compensate for the 12,000 ft offset wiped out the effectiveness of the AAA tracking system. By the time the system recovered, the attacking aircraft had passed the site. The use of VT/SC and wings level turn implemented through the thumb switch improved miss distances for the attacking aircraft.

Brulle, et al (Ref. 44) documented a fixed-base simulation conducted to determine design criteria for direct side-force control and consisted of over 2500 dive bombing runs. The airframe configuration was a simplified version of the USAF MDC Advanced Fighter Technology Integration Demonstrator (AFTI), a design having significant amounts of analysis and wind tunnel testing. Three direct side-force modes were investigated: 1) wings level turn (WLT), 2) lateral translation proportional (LT-P) and 3) lateral translational integral (LT-I). These modes were compared to conventional aircraft control for dive bombing a ground target. In addition, several advanced sights were evaluated along with the conventional fixed depressed reticle. A unique control mode, using conventional bank-to-turn control but rolling the aircraft about the fixed bomb sight line of sight (RLOS) was also studied. Earlier studies indicated that one potential reason for improved accuracy of DSFC was the elimination of the pendulum effect inherent in bank-to-turn tracking using a fixed depressed reticle. By examining the advanced sights and RLOS, this theory could be confirmed. The following discussion of the sights tested is taken from the reference:

> Fixed Depressed Sight - The fixed bomb sight for direct delivery employs no delivery system computations. The pilot's skill and judgement are used in achieving a predetermined or "canned" delivery solution. Direct bombing is accomplished with the use of a manually depressed sight reticle. Reticle depression is based on predetermined requirements which include: altitude, speed, dive angle, and weapon type. For this concept, the pilot flies the aircraft to establish the required dive angle and ground track that intersects the target. The "pipper" must intercept at its canned release conditions. The fixed roll stabilized bombing is similar except that the bomb sight reticle depression line is roll stabilized to roll through an angle opposite to the aircraft roll angle. This eliminates the pendulum motion of a depressed reticle.
>
> Future Impact Point (FIP) Sight - The FIP is a fully computed automatic bomb release system. Two bomb impact points, represented by the FIP reticle and DIP (displayed impact point) cross, are simultaneously displayed on the heads up display. The FIP reticle shows the pilot the point on the ground where the bomb impacts when released at a future time, the time being based upon a predetermined or a computed time of bomb fall. The DIP cross shows the pilot the point on the ground where the bomb impacts if released immediately. The difference between the two points as seen on the ground is range to go to bomb release which provides an indication to the pilot of time to go.

To properly use this mode of weapon delivery, the pilot maneuvers the aircraft to place the FIP reticle on the target and continues to track it thereafter using small aircraft corrections up to the time of bomb release. When the DIP cross reaches coincidence with the FIP reticle, time to go becomes zero and the bomb is automatically released if the weapons release button is depressed. Various automatic release conditions can be programmed. The release condition used for this simulation was programmed to provide a "defense clearance altitude" of 1500 ft. Immediately upon release, a 4G pullup would ensure a minimum altitude of 1500 ft.

The simulation task was to make a 30° dive bombing run on a ground target using an MK-82 low drag bomb. The aircraft was orientated such that a 90° turn was required to acquire the target. Diagrams of the delivery profiles for the fixed and FIP sights are shown in Figure 12. The Heads Up Displays (HUD) used in the simulation are illustrated in Figure 13 along with the initial condition used and a description of Roll about the Line of Sight (RLOS).

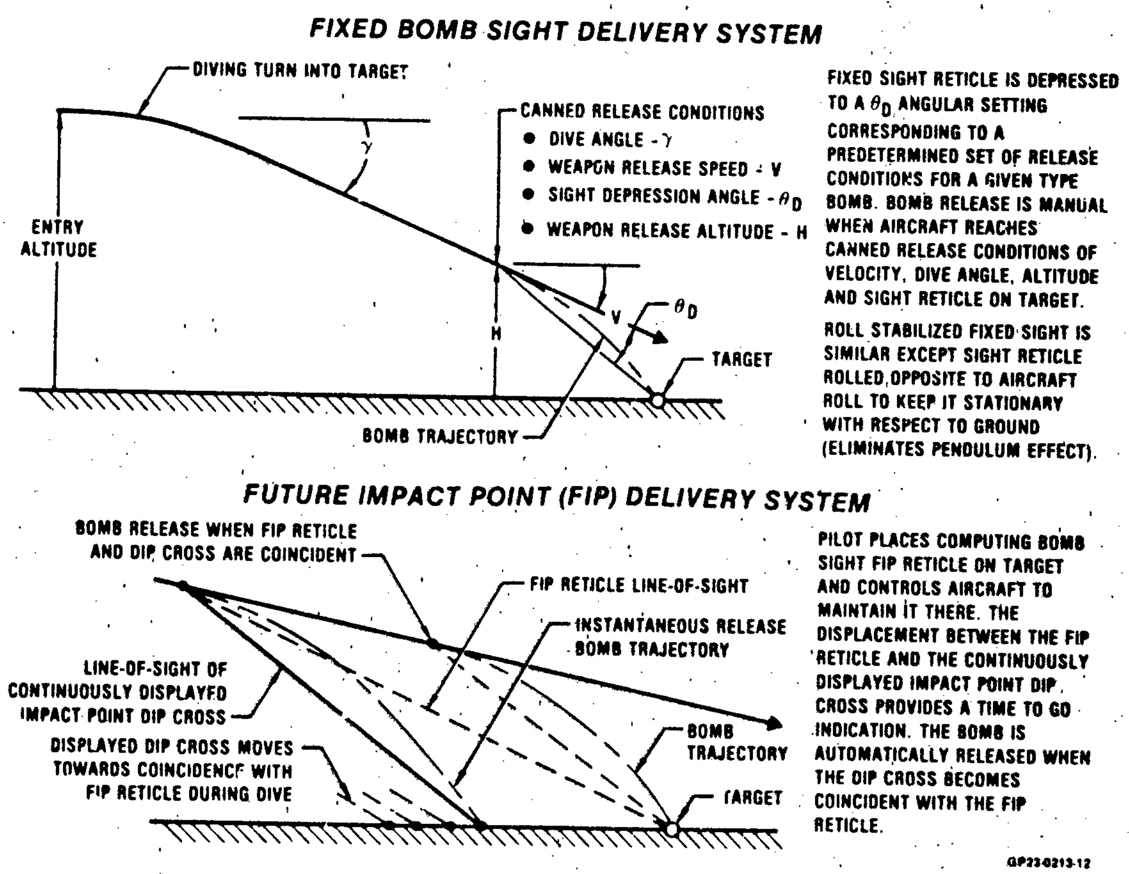
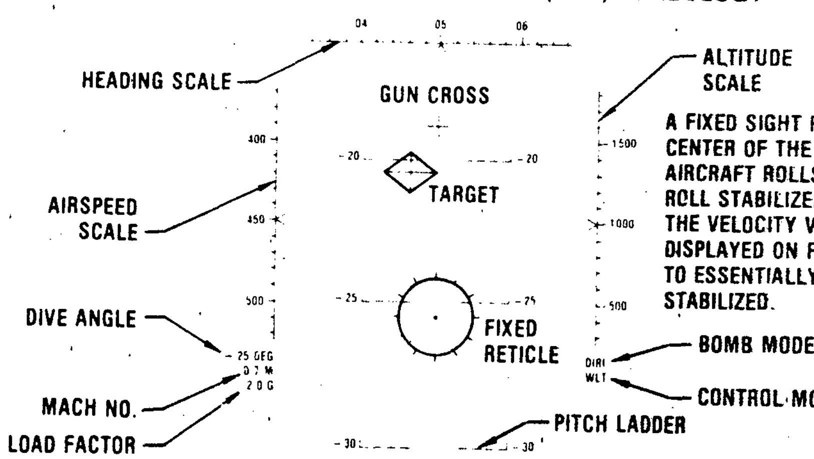


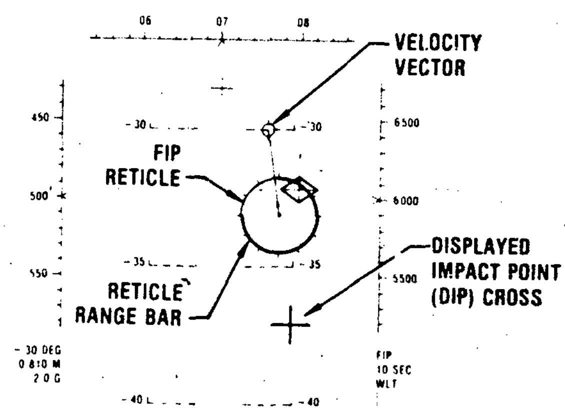
Figure 12. Weapon Delivery Systems Evaluated in Reference 44
Adapted from AFFDL-TR-76 78

FIXED AND FIXED ROLL STABILIZED SIGHT HEAD UP DISPLAY (HUD) SUMBOLOGY

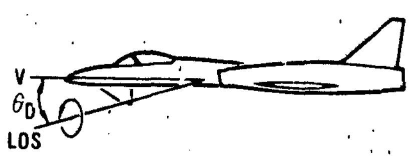


A FIXED SIGHT REMAINS IN THE CENTER OF THE HUD AS THE AIRCRAFT ROLLS. A FIXED SIGHT ROLL STABILIZED SWINGS AROUND THE VELOCITY VECTOR (NOT DISPLAYED ON FIXED SIGHT HUD) TO ESSENTIALLY REMAIN GROUND STABILIZED.

FIP SIGHT HUD SYMBOLOGY



ROLL ABOUT THE FIXED BOMB SIGHT LINE-OF-SIGHT (RLOS) CONTROL MODE



THIS CONTROL MODE ELIMINATES THE FIXED SIGHT PENDULUM EFFECT BY ROLLING THE AIRCRAFT ABOUT THE BOMB SIGHT LINE-OF-SIGHT.

FLIGHT TRAJECTORY TRACKING TIME

THE SIMULATION WAS SET UP SO THAT A 90 DEGREE TURN WHILE DROPPING THE NOSE TO THE DIVE ANGLE WAS NEEDED TO ACQUIRE THE TARGET. THE INITIAL CONDITIONS WERE VARIED TO INVESTIGATE TRACKING TIME ON BOMBING ACCURACY.

INITIAL CONDITIONS

ALTITUDE (FT)	MACH	RANGE	APPROXIMATELY TRACKING TIME (SEC)
10,000	0.8	17,000	12 (BASELINE)
9,000	0.8	15,000	9
11,500	0.8	20,000	16

GP23-0213-13

Figure 13. Displays and Test Conditions from Reference 44
Adapted from AFFDL-TR-76-78

Several conclusions of a general nature were arrived at during the simulation and analysis.

- o WLT control was liked best and the most accurate bomb scores were achieved by the pilots with this mode when using either a fixed or FIP bomb sight.
- o LT-P and LT-I were rated better, and the bomb scores were better, than a conventional control mode when using a FIP sight.
- o Pilots liked the fixed roll stabilized sight and the RLOS better, and their bomb scores were better, than with conventional control and a fixed sight.
- o A rudder pedal controller for DSFC was liked by the pilots. A thumb button on the control stick for DSFC was discarded because pilots could not simultaneously use the controller and bomb release buttons.
- o A rudder pedal controller appears insensitive to aircraft response characteristics and pilots can adapt to a large range of DSFC characteristics.
- o LT-P and LT-I flight modes are impractical for dive bombing when used in conjunction with a fixed bomb sight.
- o The variations in allowed tracking time used in this experiment had little effect on the accuracy or preference for an individual mode.

In addition several flying qualities criteria for direct side-force control were also developed.

References 45 and 46 describe the development and flight test of the F-16 Control Configured Vehicle (CCV). This aircraft offered the first true flight test of decoupled, six degree-of-freedom, flight path control. The aircraft was capable of a wide range of uncoupled motions: wings level turn (WLT), vertical path control (VPC), lateral translation (LT), vertical translation (VT), fuselage azimuth aiming (FAA), fuselage elevation aiming (FEA) and a longitudinal maneuver enhancement (ME) blending of direct lift with conventional moment control. Once the CCV mode was selected, all CCV modes except ME could be commanded by thumb pressure on a 360° isometric "coolie hat" button mounted on the side-stick controller. The lateral modes could also be controlled using the rudder pedals, depending on switch selection. Maneuver enhancement was always controlled through the sidestick controller. The pilot could select one longitudinal and two lateral (one via rudder pedal, and one via the thumb button) modes. If the same lateral mode was selected on the thumbbutton and rudder pedals, their inputs were additive. If separate modes were selected for each, the first one commanded negated any commands in the other controller. Figure 14

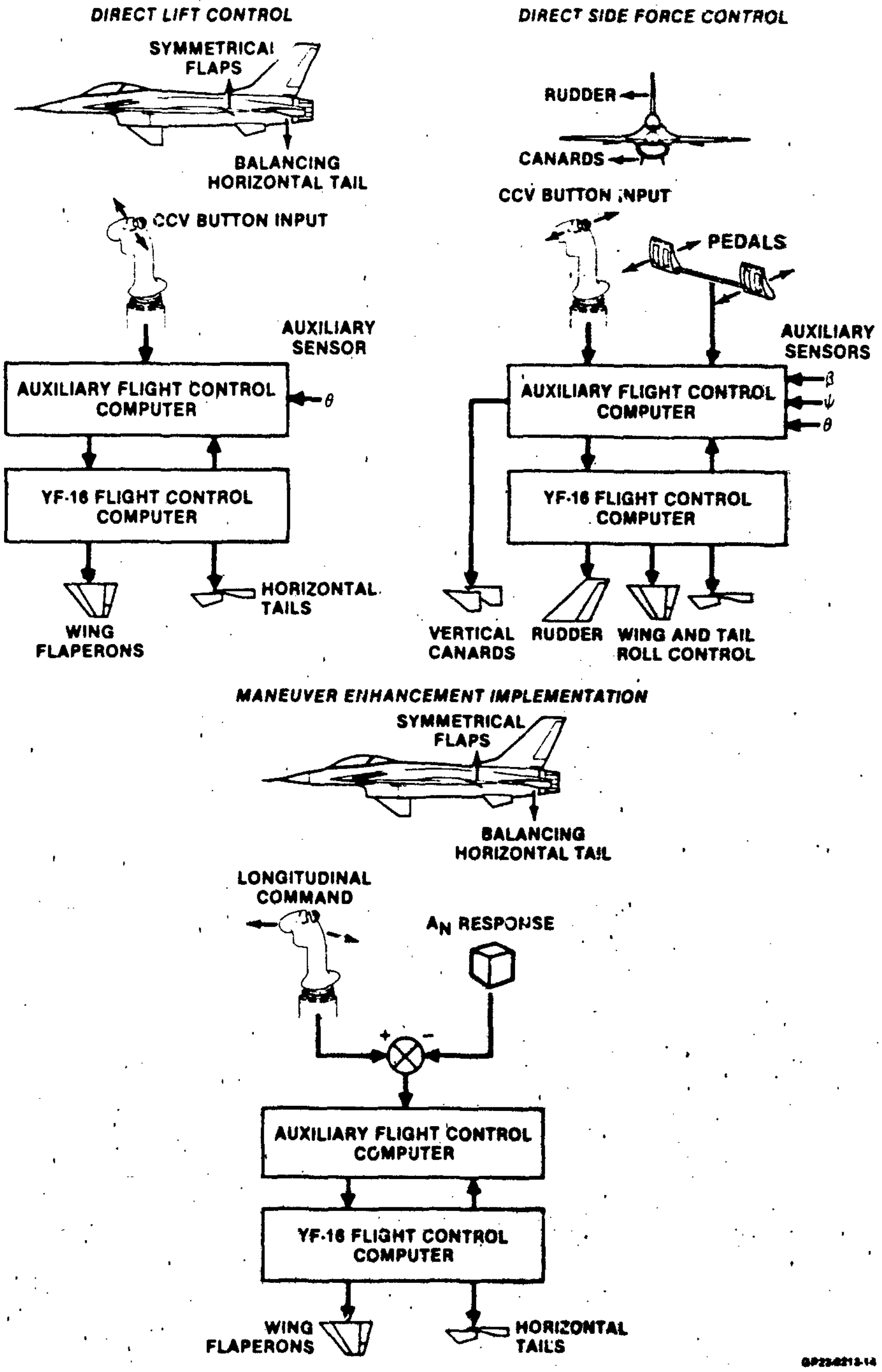


Figure 14. F-16 CCV Controller Implementation
Adapted from AFFDL-TR-78-9

illustrates the controllers evaluated. Various combinations of lateral and longitudinal uncoupled modes were evaluated. The logical mode combinations of VPC and WLT, plus FEA and FAA were rated as desirable combinations by the evaluation pilots. Mixing of CCV modes were found to be confusing to the pilots during precise tracking. Later evaluations use VPC + WLT, FEA and FAA and VT and LT.

The control modes were evaluated in air-to-ground and air-to-air tracking. The air-to-air testing utilized the Handling Qualities During Tracking (HQDT) techniques of Reference 47. The HQDT approach uses scored gunsight camera film to obtain a qualitative measure of handling qualities, response characteristics and controllability during a high-gain tracking task.

Extensive pilot comments were also used to determine the utility of the various control modes. Target aircraft were F-4's and T-38's. A limited number of runs placed the F-16 CCV as the target aircraft in order to evaluate the defensive capabilities of the uncoupled control modes. The potential for defensive maneuvering was demonstrated, however the pilots desired 2 to 3 g's of direct force control. For air-to-air tracking the pilots preferred the use of VPC and WLT to other uncoupled modes. The rudder pedals were preferred for control of WLT. A strong preference was expressed to separate the pilot inputs in terms of control device and response axis. For large-scale air combat maneuvers and air-to-air tracking, the pilots ranked the modes as follows:

1. WLT and VPC (2-3 g's authority required)

2. FAA and FEA (automatic fire/flight control preferred)

3. LT and VT (very limited use due to authority availability)

The air-to-ground tasks consisted of dive bombing and strafing maneuvers. The tasks used are shown in Figure 15. Based on pilot opinion, the following conclusions were reached:

1. Wings Level Turn was judged to be the most worthwhile of the CCV modes for air-to-ground operations because it:

   o Eliminated sight pendulum effects during maneuvering

   o Allowed quicker line-up on ground targets

   o Simplified the tracking of moving targets.

2. In general, there was little foreseeable need for the Vertical Path Control capability in air-to-ground operation. It has the ability (as does Maneuver Enhancement) to reduce the altitude loss during dive recovery, but it is more effective because the incremental load factor is retained in the VPC than ME mode instead of washing out as the recovery progresses.

3. Lateral Translation showed greater potential in air-to-ground than in air-to-air tasks. It was judged to be effective in cancelling crosswind effects in strafing and dive bomb operations and during landing approach.

4. The pointing modes exhibited potential for all low-level strafing of stationary targets. Elevation Pointing was effective in increasing the minimum altitude during recovery from strafing runs. Azimuth Pointing was endorsed for improving the aiming accuracy during dive bombing in crosswinds and during low angle strafing of moving targets.

TASK
AIR-TO-GROUND GUNNERY
● TRACKING (30 SEC)
● BANNER STRAFE
● AREA STRAFE
● 30 MPH VEHICLE
● 60 MPH VEHICLE
AIR-TO-GROUND GUNNERY
● TRACKING (30 SEC)
● OPERATIONAL D/B
● 60 MPH VEHICLE
● PULL-UPS
OTHER TASKS
● ROAD RECON
● APPROACH AND LANDING (OPINION)

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Figure 15. F-16 CCV In-Flight Evaluation Tasks
Adapted from AFFDL-TR-78-9

The rudder pedals were the preferred controller for the wings level turn mode. However, the system appeared too sensitive for terminal precision tracking at 400 KCAS near the ground. Maneuver Enhancement was endorsed by the pilots for all missions examined, both for improved normal acceleration response and for gust alleviation. Also, all pilots indicated a preference for integrating the fuselage aiming modes with an automatic fire/flight control system to simplify the piloting task. Reference 46 contains specific recommendations to achieve more "task oriented" improvements in terms of controllers, control laws, and task realism. In particular the reference lists:

Controller Improvements

Simplify the pilot controllers for air-to-air tracking tasks by providing:

1. "Beep" correction capability via an on-off switch controller and integral commands for pointing modes

2. Blending of CCV and basic pilot commands on the conventional control stick.

Optimize controller mechanization for air-to-ground weapons delivery tasks through use of:

1. Nonlinear and/or selectable force gradients

2. Mode authorities matched to the specific task.

Improved Realism of Flight Evaluations

The following actions are recommended to enhance the operational realism of flight evaluations:

1. Utilize a state-of-the-art sight system including specific air-to-air and air-to-ground fire control modes.

2. Evaluate operational effectiveness of "task oriented" modes by delivering actual ordnance for score.

3. Remove CCV maneuvering limits. Engage in mock air-to-air combat against adversary of similar conventional performance.

Wood, et al (Ref. 48), describe the Air Force evaluation of the F-16 CCV aircraft of Reference 46. They indicate that the test results demonstrated the potential for improving the accomplishment of almost any fighter operational task. Some of the benefits were based on extrapolation to higher levels of CCV control authority and task optimized controller characteristics. Recommendations indicate the need for testing larger authority modes tailored to the evaluation task and interfaced through the fire control system. Important areas for future development of uncoupled modes, in order of priority, were:

1) Air combat maneuvering - area of greatest overall benefit

2) Air-to-air tracking - area of greatest low-authority mode potential

3) Air-to-surface - improved lateral steering and survivability

4) Other tasks - improvements in routine or less critical tasks.

If the number of uncoupled modes was to be limited, the following list indicated preference in order of importance.

1) Wings Level Turn

2) Vertical Path Control

3) Fuselage Elevation Aiming

4) Fuselage Azimuth Aiming

5) Maneuver Enhancement

6) Lateral Translation

7) Vertical Translation

The incorporation of limited vertical path control using the centerstick was suggested.

Also, the use of fuselage aiming as part of an automatic fire/flight control system was indicated as being preferable to manual control. The report also recommends that future investigations limit the number of participating pilots and allow these pilots ample practice with the aircraft controllers. Considerable emphasis on evaluating pilot workload will be required with HQDT type quantitative data being used to identify large differences between test parameters.

References 49, 50 and 51 describe the design and development of the AFTI/F-16 multimode digital flight control system. Reference 49 describes the preliminary development and simulation of the original configuration. Due to time constraints, the direct force modes were not evaluated by pilots in combat. References 50 and 51 address the further refinement and definition of the configuration. Reference 51 describes the latest version of the AFTI/F-16 and will be discussed here. The overriding requirement for the flight control system design was to provide task-tailored multi-mode control functions. These functions include:

- Normal - used for takeoff, cruise and landing and for the performance of secondary mission tasks such as refueling and formation flying.

- Air-to-air - used throughout the air combat envelope to provide rapid maneuvering during intercept and precision tracking.

- Air-to-surface gunnery - provides rapid and precise fuselage pointing for strafing ground targets.

- Air-to-surface bombing - provides precise control of the aircraft velocity vector and enables the employment of effective control strategies to increase survivability.

Each of the modes is comprised of a "standard" and a "decoupled" mode. The standard modes use conventional moment control to maneuver the aircraft. The pilot interface is through three controllers - right hand sidestick, left hand linear track throttle, and the rudder pedals. The sidestick controller is of the limited displacement type and incorporates a paddle switch for selecting either standard or decoupled modes. The horizontal throttle also has a twist motion available for control of longitudinal uncoupled motion. The pilot selects one of the multimodes (normal, air-to-air, air-to-surface bombing, or air-to-surface gunnery) which automatically reconfigures the flight control laws, Heads Up Display, fire control computer, stores management system and radar to the proper status. The desired functions for the controllers are then determined by selecting either standard or decoupled modes. The controller functions are defined as follows:

Standard normal mode

Sidestick (pitch) - normal acceleration command
Sidestick (roll) - roll rate command
Rudder Pedal - rudder deflection command
Throttle twist - none

Decoupled normal mode

Sidestick (pitch) - flight path maneuver enhancement
Sidestick (roll) - roll rate command
Rudder pedal - lateral translation acceleration
Throttle twist - vertical translation acceleration

Standard air-to-surface bombing

Sidestick (pitch) - normal acceleration command
Sidestick (roll) - roll rate command
Rudder pedals - wings level turn command
Throttle twist - none

Decoupled air-to-surface bombing

Sidestick (pitch) - flight path maneuver enhencement
Sidestick (roll) - roll rate command
Rudder pedals - wings level turn command
Throttle twist - vertical path acceleration control

Standard air-to-surface gunnery

Sidestick (pitch) - pitch rate command
Sidestick (roll) - roll rate command
Rudder pedals - wings level turn command
Throttle twist - none

Decoupled air-to-surface gunnery

Sidestick (pitch) - pitch rate maneuver enhancement
Sidestick (roll) - roll rate command
Rudder pedals - fuselage azimuth aiming
Throttle twist - fuselage elevation aiming

Standard air-to-air

Sidestick (pitch) - pitch rate command
Sidestick (roll) - roll rate command
Rudder pedals - wings level turn command
Throttle twist - none

Decoupled air-to-air

Sidestick (pitch) - pitch rate maneuver enhancement
Sidestick (roll) - roll rate command
Rudder pedal - fuselage azimuth aiming
Throttle twist - fuselage elevation aiming

The maneuver enhancement modes are a blend of conventional and vertical path control to provide an enhanced coupled maneuvering response to pilot inputs to the sidestick. Due to limited control power available on the AFTI/F-16, the uncoupled motions are incorporated for use in vernier tracking and small-amplitude corrections to the flight path. The AFTI/F-16 has been extensively tested in man-in-the-loop simulations using full non-linear equations of motion and a very detailed aerodynamic data set developed from extensive wind tunnel testing.

Sammonds and Bunnell (Ref. 52) conducted a motion-base simulation experiment to determine flying qualities criteria for wings level turn in a dive bombing delivery of free fall weapons. A conventional six-degrees-of-freedom mathematical model was developed to represent a state-of-the-art fighter aircraft having flying qualities similar to those of the F-15. The WLT mode was modeled as a transfer function relating lateral acceleration to rudder-pedal deflection. Feedback was used to ensure minimal sideslip angle. While not simulating any real aircraft or design, it was felt this method allowed variation of important handling qualities parameters and allowed the study of pure, uncoupled responses. The pilot was given a Heads Up Display (HUD) with a fixed, depressed reticle sight (Figure 16). The task was an air-to-ground delivery of an unguided bomb. The task began with a roll onto the target from a 90° heading offset at an altitude of 10,000 feet. The desired release conditions were a 30° dive angle, at 5000 feet with a velocity of 1200 ft/sec. The high velocity was used with the initial and final altitudes to provide a task that would not be easily accomplished with a poor system. The average tracking time before release was 4 to 5 seconds. The pilots were given sufficient practice to become familiar with the delivery profile. The target was a black and

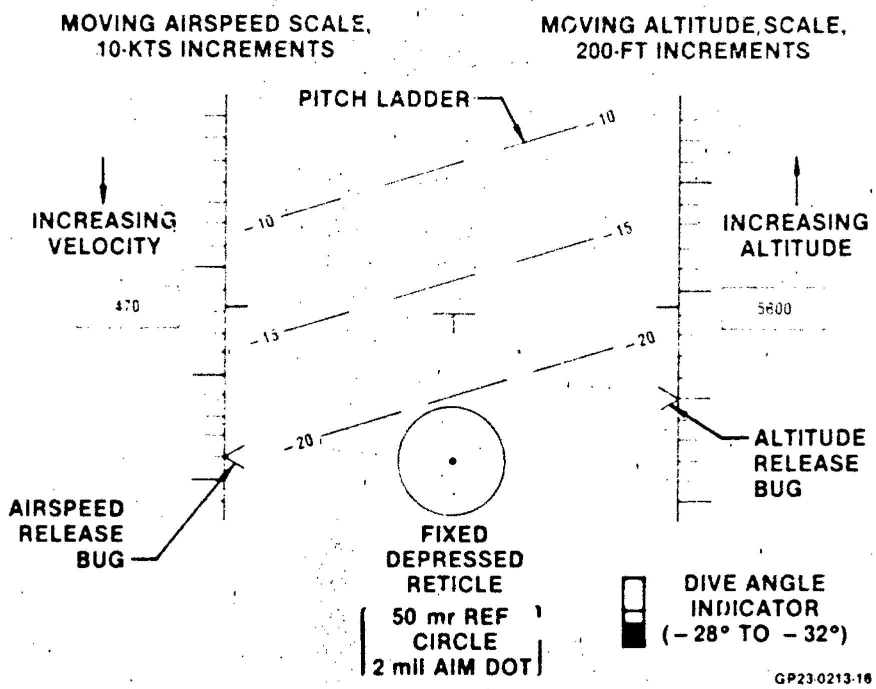

Figure 16. Head Up Display (HUD) Used for Dive Bombing Task of Reference 52

white bulls-eye of concentric circles 2000 feet in overall diameter. Approximately 50% of the time, a light in the center of the target would come on after the pilot had started his run. The light signaled the pilot to bomb a secondary target (a white dot) offset 1000 feet laterally from the primary target. This necessitated a heading change of about 12° in 4 seconds. While not a realistic operational maneuver, the secondary task was chosen to subject the WLT mode to a severe heading change in order to evaluate its gross maneuvering capabilities. Figure 17 illustrates the primary and secondary targets as well as the bombing task flight profile. While mainly a handling qualities simulation, an effort was made to determine the control authority required. Simulated authorities of .5, .75, and 3 g's were tested. The .5 g level was found to be inadequate for the task. The .75 g level was adequate for the primary task but did not have enough authority to reach the secondary target in time. The 3 g authority level provided more than enough control power for both tasks. Analysis of the time histories showed that a maximum lateral acceleration of 2.5 g's was commanded momentarily. However, 50% of the time no more than 1 g laterally would be required. In a comparison with the conventional control airplane it was almost impossible to accomplish the secondary task with conventional bank-to-turn control due to the small amount of time for target alignment. The consensus of the pilots was that WLT with good response characteristics greatly simplified the lateral tracking task and allowed more attention to the longitudinal task.

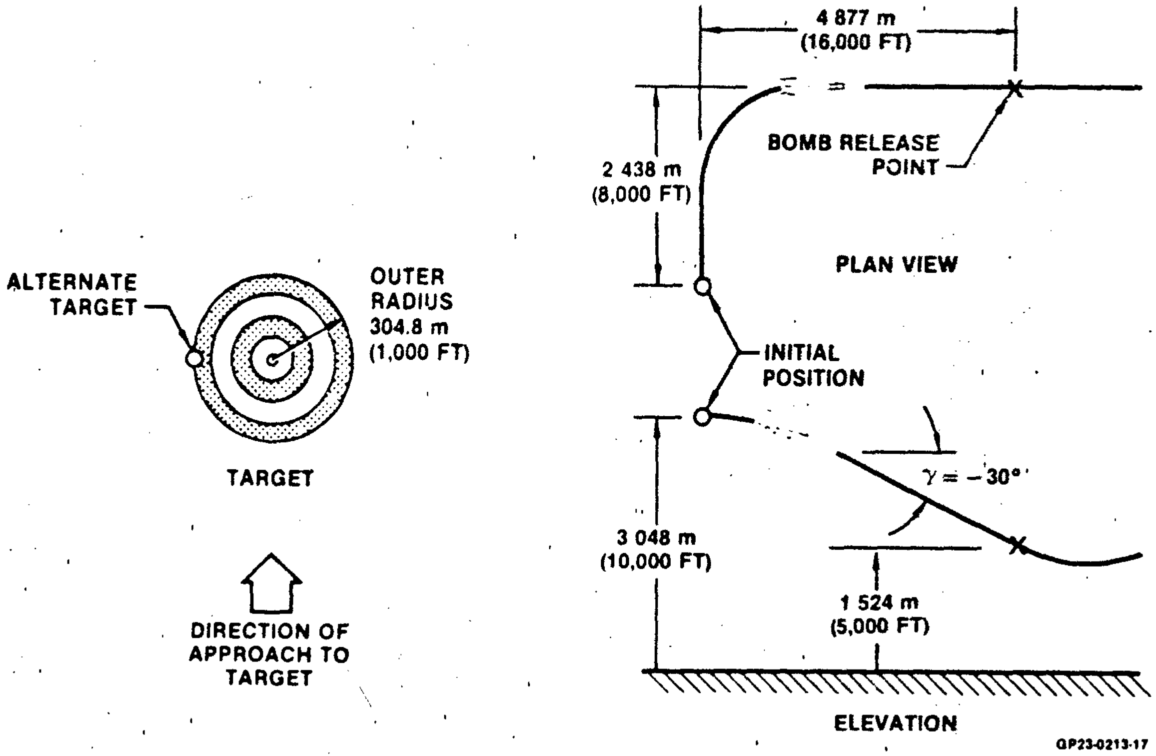

Figure 17. Bullseye and Alternate Targets and Task From Reference 52

Reference 53 describes the simulation analysis of a fighter aircraft incorporating unorthodox control forces in air-to-air missions. The configuraton was the MCAIR vectored lift fighter (VLF) equipped as shown in Figure 18. The configuration has shown the capability to double the close-in combat effectiveness of a baseline aircraft possessing only conventional control. The simulation task was air-to-air combat against two threat aircraft of equivalent maximum sustained and instantaneous normal load factors at all flight conditions and with identical electronics, armament, and pilots as the VLF. In addition to the direct force modes (DFM) the configuration was also tested with vectored thrust Post Stall Technology (PST) in addition to DFM. The thrust vectoring allowed attitude control at airspeeds below 270 knots and angles of attack up to 80°. The simulation was structured such that the advantages due to each of the advanced modes could be analyzed separately. Many of the modes individually showed minimal usefulness, but when combined, large increases in capabilities were noted. The direct forces are provided by deflection of the variable incidence wing (the outer portion of each wing is movable), elevator, and rudder.

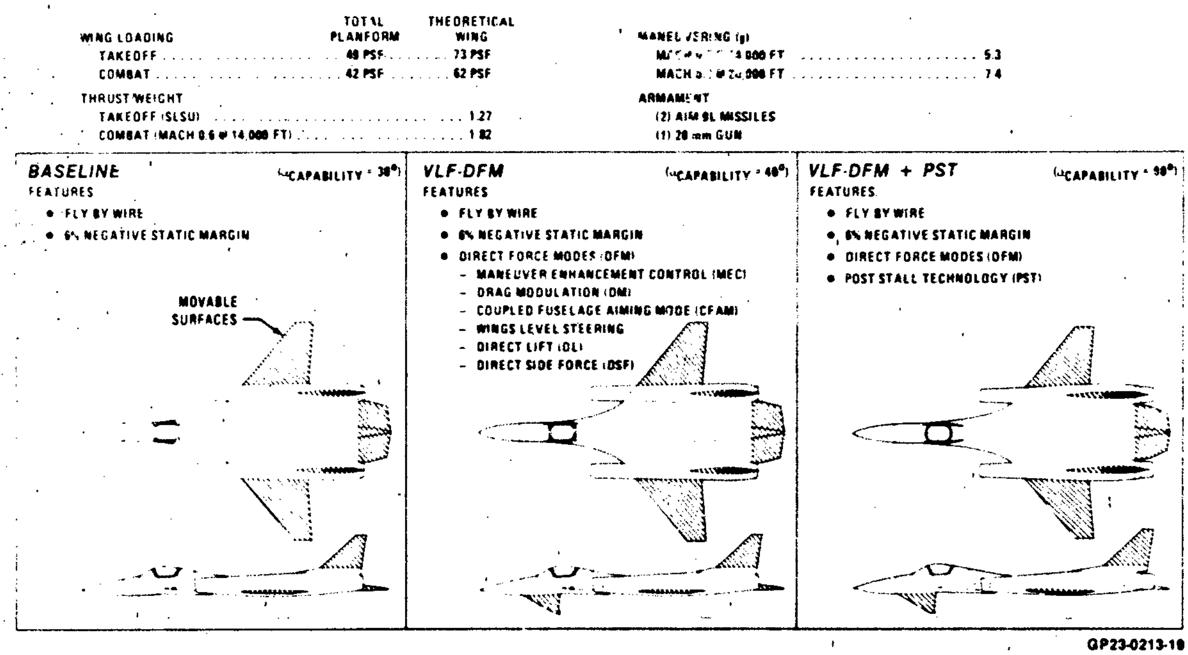

Figure 18. Simulated Test Configurations from Reference 53

Most of the 6-DOF modes defined at the beginning of this report were simulated. An additional factor was the high roll capability at high angles of attack. This allowed, for instance, 90 degrees bank angle in 1 second at 25 degrees angle of attack and 9 g's. The pointing modes were incorporated in an automatic fire/flight control system. At Mach .9, 10,000 feet altitude, 1 g of wings level turn and lateral translation authority was simulated. Drag modulation produced .3 g's tangential deceleration at Mach .9, 10,000 feet, i.e. it was about three times more effective than a conventional speed brake. The simulation included a Heads-Up Display with appropriate symbology for the coupled fire/flight control modes.

Roll control due to the variable incidence wings was the most significant factor in gross maneuvering. Post stall technology was useful in enhancing maneuvering capability near $C_{L_{max}}$ below corner speed. Drag modulation, activated by the speed brake switch, was the second most significant unorthodox control mode in producing air superiority in gross maneuvering. The coupled fire/flight modes produced more than ten times the gun kills of the baseline aircraft, which required conventional manual tracking by the pilot. Lateral translation acceleration control was of little significance as an isolated capability in combat. Longitudinal maneuver enhancement produced no apparent advantage in fine tracking (it was conceived primarily as a ride enhancer, and this was a fixed-base simulation). Its advantages in gross maneuvering were small but measurable.

Binnie and Stengal (Ref. 54) tested several side-force command modes implemented on the Princeton 6-DOF variable response research aircraft (VRA). Wings level turn and lateral translation modes were tested. These were commanded by inputs to a stick-mounted thumb switch, the lateral stick and rudder pedals. Various blendings of sideforce with conventional ailerons and rudder were investigated. Proportional translation commands were controlled by the thumb lever while translation rate commands were available using the thumb-trim-switch. Wings level turn could be commanded using the rudder pedals when this mode was engaged. Side-force roll modes allowed control of translation with lateral stick. The dual interconnect mode blended sideforce commands with the normal stick and rudder pedal inputs. Proportional control of translation was preferred due to the predictability of the response. A military evaluation pilot preferred the "snappy" response of the WLT mode commanded by the rudder pedals. A civilian (general aviation) pilot preferred control of lateral translation. The side-force roll modes were not as well liked by either pilot. The dual interconnect mode degraded pilot ratings. In general, pilots preferred side-force command modes that were uncoupled from conventional stick and pedal inputs since they interfered less with learned control techniques.

Hoh, et al (Ref. 26) performed a flight test experiment to aid in the development of handling qualities for aircraft with independent six-degree-of-freedom control. A wings level turn mode commanded by rudder pedal deflection was implemented on the Princeton VRA (Ref. 54). Visual responses were tailored to be typical of a modern fighter aircraft performing air-to-air tracking at Mach .8. Acceleration cues did not match this flight condition due to the 105 kt maneuvering speed of the VRA. Use of the VRA's .5g side force acceleration capability corresponded to a lateral acceleration of 2.5 at Mach .8. Various degrees of roll and yaw coupling were also tested. Results indicated that the use of conventional controls for gross maneuvering and WLT for fine tracking was a desirable technique.

Moorhouse, et al (Ref. 55) performed a motion based simulation to investigate the use of direct force modes for defending against gun attack. The direct force capable airplane had the response characteristics and capabilities of the F-16 CCV (Ref. 45). In the initial simulation pilots tracked an "uncoupled" target programmed to move in either vertical or lateral translations with various acceleration levels. The pilots tracked these motions using the control modes of the F-16 CCV flight control system. Vertical translation between 1/2 to 4 g's showed no consistent effect on task difficulty. However, lateral translations showed a much larger increase in task difficulty. Considerable pilot compensation was required to track as little as 1/2 g of lateral acceleration. These results indicate there is little defensive capability associated with vertical translation while as little as 1/2 g of lateral translation greatly increases defensive potential. In a follow-on simulation pilots flew a conventional configuration equipped with various levels of Integrated

Fire/Flight Control capability against a direct force capable target possessing response magnitudes similar to the F-16 CCV. The targets flew a "canned" flight path stored earlier by having pilots fly the CCV capable aircraft and applying direct force and conventional control inputs at predetermined times. These responses were stored and used to drive the target motion for the IFFC simulation. The IFFC capable aircraft was able to track the target through any combination of rapid reversal maneuvers. These results indicate no benefit in defensive capabilities for an aircraft having F-16 CCV direct force modes when attacked by an aircraft equipped with an integrated fire/flight control system.

There are several ongoing studies of controllers for uncoupled motion. A four axis controller incorporating twist and heave control inputs along with the normal pitch and roll axis is being evaluated for use in helicopters (Ref. 56). Efforts of this type should be followed in the future to take advantage of any possible application to airplane controllers.

Some potential problem areas have also been identified. In Ref. 46 at least one pilot indicated concern over the response of the F-16 CCV when he encountered heavy turbulence with the maneuver enhancement mode engaged. He found the rapid movement of the flaperon to be disconcerting. Additonally, there appears to be some concern over the onset rate of normal load factor and pitch rate in some of the maneuver enhancement modes. High onset roll rates of conventional aircraft have been shown to cause degradation in pilot acceptance (Ref. 57).

Centrifuge experiments were conducted to investigate the effects of lateral accelerations on pilot tracking abilities (References 58 and 59). Results indicate that pilot restraints will be required for lateral accelerations in excess of 1 g. Additionally, significant control cross-coupling and inadvertant inputs to the sidestick controller, rudder pedals and throttle were noted due to increasing lateral accelerations. Any future investigations of direct side-force should consider these problem areas. A review of these results appear in the literature summary sheets in Appendix A.

9. COMMENTS ON THE LITERATURE - A wide variety of reports have been examined covering elements of manual control and the application of six-degree-of-freedom control to aircraft mission effectiveness. In evaluating 6-DOF control on a wide range of aircraft (from heavy transports to high performance fighters) many apparent contradictions on the degree of benefit can be identified. However, many areas of agreement in general principles do surface:

1. The use of direct vertical and side-forces has the potential to simplify landing tasks for all aircraft types.

2. The various forms of maneuver enhancement have generally been accepted as beneficial.

3. In military applications, the use of wings level turn shows the greatest potential in air-to-surface bombing accuracy improvements.

4. Automatic implementation of the fuselage pointing modes would be their best application.

5. No optimum method of controlling these 6-DOF modes has been found. The use of the rudder pedals for lateral uncoupled modes has been found to be acceptable, however.

6. No study has been attempted to define suitable criteria to aid in the design of controllers for aircraft capable of high authority, uncoupled motion.

For those flight control modes blended with conventional response on a standard cockpit controller, the control forces limits listed in (Ref. 67) would still apply as would other standard controller requirements. However, it should be remembered that uncoupled control means multi-surface control. As a result, control paths will probably be by wire or light rather than by direct mechanical linkage. Additionally, a computer will probably determine the necessary surface deflection at each flight condition. Therefore, those requirements dealing directly with characteristics of mechanical linkages may be downplayed accordingly.

Two studies, References 41 and 44, performed the only detailed variance of controller parameters. Hall (Ref. 41), performed several iterations on rudder pedal friction and gradient characteristics in his T-33 simulation of the Northrop A-9A. He found that a breakout/hysteresis combination of 3.5/3.0 lbs was superior to a combination of 7.0/6.0 lb. The pilots preferred a pedal gradient of 32 lb/in. Problems in implementing the wings level turn on the NT-33 and the relative impurity and low authority of the projected A-9 system cast some doubts on the usefulness of these data.

Brulle, et al (Ref. 44), performed a handling qualities experiment for three types of lateral decoupled control as described in the literature review. Several rudder pedal sensitivities were examined for a fixed set of rudder pedal characteristics typical of a high performance fighter.

In most cases where rudder pedals were used, the gradients and friction characteristics were those associated with normal pedal function in a conventional fighter aircraft.

Attempts to develop tentative criteria based on a review of the available literature are hampered by the myriad of different controllers used in these studies. Often in these studies the controller characteristics have not been described in any detail since the experiments were aimed at proving viability of uncoupled control rather than desirability of the controller. Also continued references to the inadequacy of controllers in the various references indicates that a satisfactory method has not been found.

10. INDUSTRY AND GOVERNMENT SURVEY - In addition to a review of available literature, organizations currently involved in aircraft and controller design have been contacted in order to gather information concerning current and planned efforts in this area. Also unpublished ideas and opinions about the control of uncoupled aircraft motion are being solicited. Letters describing the effort, and requesting any suggestions or comments, were sent to organizations active in controller and aircraft design and evaluation. Copies of the letter are included in Appendix B. No response was received to the letter.

Discussions have also been held with personnel of Systems Technology, Inc., Douglas Aircraft, NASA Dryden Flight Research Center, the Air Force Flight Test Center, and General Dynamics (Fort Worth) concerning their experiences with controllers and the control of aircraft capable of uncoupled motion. The briefings included the test pilots who will be conducting the AFTI/F-16 flight test program. These pilots have extensive simulation experience with that configuration. A report of these discussions is included in Appendix C.

SECTION III
MISSION EFFECTIVENESS

Despite all the research and testing in the area of uncoupled motion control, there are still serious doubts about the usefulness of these modes in the operational environment. In military applications, the advantages of unconventional control modes would seem to be an increase in aircraft maneuverability and weapon delivery accuracy. Because the modes are generally transient or of low steady-state authority, their advantages would be seen in a short range combat engagement. Rossiter (Ref. 60) points out that the greatest demands on maneuverability occur when an aircraft becomes involved in one-versus-one close combat. The developing technologies of identification of friendly and hostile aircraft beyond visual range (BVR), and the capability to launch weapons without ever seeing the target theoretically reduce the need for increasing aircraft maneuverability. In this type of situation, in the majority of occasions on which an aircraft is destroyed, the pilot would be unaware that he is under attack. The first step to increase effectiveness would then be the use of an improved tactical evaluation and control system and/or provision of an effective onboard warning system to increase pilot awareness of the presence of hostile aircraft. Once this awareness is achieved, then the maneuvering abilities of the aircraft come into play.

Hill (Ref. 62) investigates aircraft requirements for conflict in Central Europe. He indicates that it is generally accepted that the Soviets will use electronic countermeasures (ECM) to a large extent. This use of ECM will be combined with inadequate identification systems. The tremendous radiative power (approaching radio frequency pollution) which will be produced by the many ground and airborne radars and command and control communications of all the involved nations could easily reduce the effectiveness of long-range radar and air-to-air missiles. Aircraft would be forced to act autonomously, depending on non-jammable infra-red (IR) systems for search and ultimately on visual identifications. The limited range of IR in the moisture-laden weather of Europe has several impacts on tactical requirements. Of importance to this discussion is the decreased range that can be expected before combat is initiated. Thus even with sophisticated radar and identification systems, short range, maneuvering combat capability may still be a requirement for the operation effectiveness of combat aircraft.

Henni (Ref. 63) examines combat aircraft maneuverability as it applies to air-to-ground and air-to-air operations in Central Europe. Maneuverability is defined as the ability to change the direction and magnitude of an aircraft's velocity vector. For air-to-surface operations, survivability will depend on the capability to fly very low at high speed. During a mission the maneuvering capabilities of an aircraft in relation to airspeed determine how closely the pilot can follow the terrain in order to avoid infra-red surface-to-air missile (I.R. SAM) systems. When avoiding obstacles and closely following the terrain, the ability to vary altitude without greatly altering aircraft attitude would improve the pilot's vision and inspire the confidence necessary at very low levels. Vertical direct force generation of a large enough authority would provide this capability. Lateral direct force generation allows the pilot to avoid obstacles without having to bank and turn the aircraft, a maneuver which is dangerous because of the limited realistic very low level flight training attainable in Central Europe. The use of direct force controls in combination with advanced fire controls will add finesse to the aiming of unguided weapons. For air-to-air engagements, Henni felt that current fighters, such as the F-16, approach the normal load factor that a pilot can endure. Improvements then must come from extending the flight envelope. Additionally, new technologies of direct force and thrust vector control will play a part in further improvements in maneuverability.

In this report, we have not tried to prove conclusively that uncoupled, six-degree-of-freedom control is an absolute necessity. Rather, we have shown that there is sufficient interest in this technology to recommend further study. It follows that criteria for the design of controllers for manual control and recommendations for automatic implementations will be required to aid in the design of future aircraft systems attempting to utilize uncoupled motion. Based on the literature survey several recommendations for the use of uncoupled aircraft motion can be made.

First, wings level turn has demonstrated the potential for increasing accuracy and survivability in the air-to-surface delivery of conventional weapons. The use of unguided weapons may seem contrary to new developing technologies. However, in a conflict of any magnitude or duration, the ability to deliver accurately large quantities of these readily available weapons must be considered. The use of vertical path control assists the pilot in the pull-out phase of the dive bombing maneuver, allowing operations at a lower altitude.

The use of the translation and fuselage pointing modes has offered several advantages in air-to-surface strafing. Lateral translation accounts for crosswinds while elevation fuselage aiming allows a firing solution at a lower altitude for a given slant range to the target.

Wings level turn and, to a lesser extent, vertical path control and the translation modes have shown potential usefulness in the nulling of steering errors in air-to-air engagements. The automatic fuselage aiming modes allow the pilot to concentrate on the gross maneuvering task while the fire/flight control system accomplishes the fine tracking requirements. A potential decrease in pilot workload results. Given enough authority, the use of uncoupled motion would seem to be beneficial as a defensive tactic, especially against a conventional aircraft under manual control.

The vertical and lateral translation modes have shown promise in simplifying the landing task for all classes of aircraft. This reduction in pilot workload increases safety, and decreases touchdown dispersion in this task. The increased precision of landing has significant implications for carrier-based aircraft and for other aircraft operating from short fields due to runway denial or using unimproved airstrips. Landing speeds may be reduced because aircraft speed is no longer the only parameter affecting path-to-attitude bandwidth.

In many studies, the blending of uncoupled responses with conventional control has resulted in quicker, more precise aircraft control. Also, improved gust and turbulence response has been noted. This improvement in ride qualities is potentially important in high speed, low level flight resulting in increased pilot confidence and comfort.

1. PILOT WORKLOAD - There is legitimate concern from many pilots that the incorporation of manual control of uncoupled aircraft motion may significantly increase the workload in accomplishing a given task. This would be an intolerable situation in a period where increasing demands are being placed on the pilot's allocation of time.

Reference 64, in describing the system designed for the AFTI/F-15, indicates that the incorporation of advanced technologies reduced pilot workload in many areas as compared to conventional aircraft (i.e., the F-15). However, much of this increased available time was spent in utilizing additional capabilities of the system.

An extensive time line analysis for the AFTI/F-16 was carried out in Reference 50. Through the use of a multi-mode flight control and data management system, it was determined that pilot workload was within acceptable levels.

The task tailored multi-mode flight control system allows the aircraft flight control laws and displays to be tailored to the task at hand. By carefully selecting the control capabilities and their distribution to the controllers available to the pilot, the designer can minimize the impact on pilot workload levels. Such a system must also display the data required by the pilot for a specific task.

A simplified example of time line analysis for an air-to-ground weapons delivery is illustrated in Figure 19. Cognitive workload refers to the time spent by the pilot in processing the information available to him and determining the necessary corrective actions. Psychomotor workload pertains to the time spent by the pilot in implementing the corrective actions determined during the cognitive task. From this illustration, we see that

	APPROACH	CURVILINEAR TRACKING	TRANSITION	STRAIGHT TRACKING	PULL-OUT
PSYCHOMOTOR TASKS	COMPENSATORY: ● STABILIZE ATTITUDE ● MAINTAIN ALTITUDE	PRECOGNITIVE: ● ROLL INTO TURN COMPENSATORY: ● HOLD BANK ANGLE ● MAINTAIN ALTITUDE	PRECOGNITIVE: ● ROLL TO ~ 120° ● PULL DOWN TO RUN-IN LINE ● ROLL OUT IN DIVE	COMPENSATORY: ● NULL OUT SIGHT ERRORS	PRECOGNITIVE: ● PULL UP @ HI g COMPENSATORY ● MAINTAIN CLIMB RATE TO DESIRED ALTITUDE
PROCEDURAL AND COGNITIVE TASKS	● FOLLOW CHECKLIST ● MODE SELECTION ● MONITOR TACTICAL SITUATION ● MONITOR AIRCRAFT STATE	● CONT CHECKLIST ● ARM WEAPON ● CONT MONITORING TACTICAL AND AIRCRAFT STATE ● ESTIMATE TIMING OF TRANSITION	● ESTIMATE TIMING OF ROLL OUT TO TARGET HEADING	● ESTIMATE WEAPON RELEASE TIMING	● MONITOR TACTICAL SITUATION ● MONITOR AIRCRAFT STATE

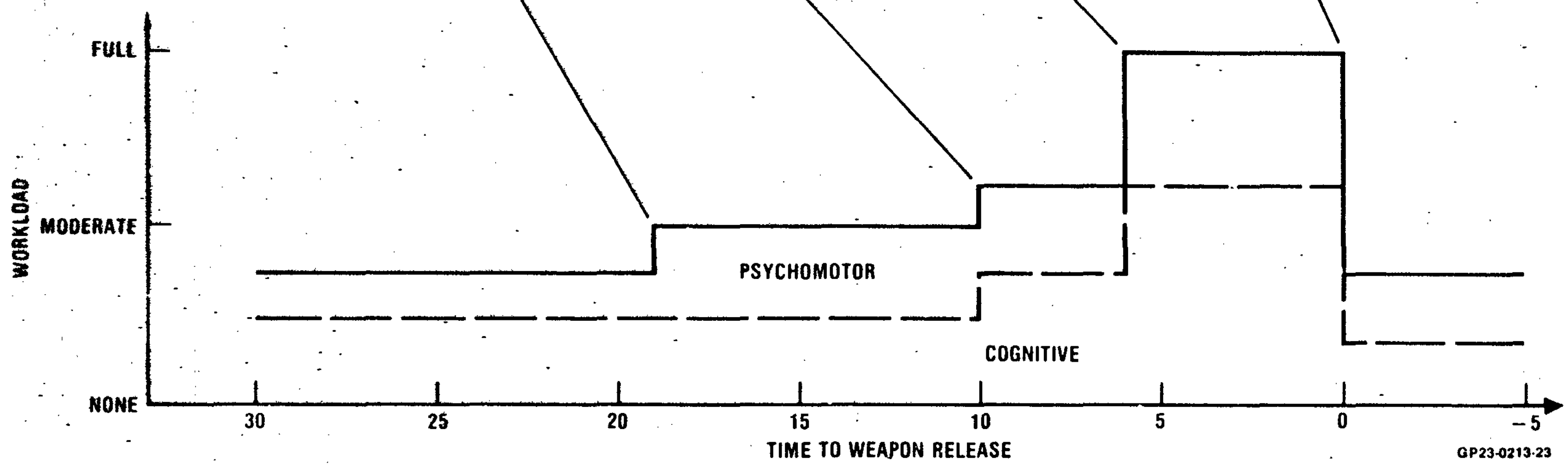

Figure 19. Example Time Line Analysis for Air-to-Ground Mission

the highest workload levels occur during tracking. Here the pilot is determining and implementing the actions required to null out errors and time the release of the weapon. This holds true whether uncoupled motion capability is available or not. In discussions with pilots active in the AFTI/F-16 simulations, the major increase in workload seemed to be in determining which controller to utilize. Thus, something that should be a psychomotor task (i.e., controller inputs) becomes part of the cognitive task, thereby increasing pilot workload. The most obvious way to minimize pilot workload in this situation would be to allow the necessary inputs to become a natural pilot response. This would require utilization of uncoupled motion capabilities in an operational environment so that the necessary control strategies and techniques can be developed. Additionally, an automatic weapons release system would determine the proper time of weapons release. Freed of the cognitive task of determining proper release time, the pilot can concentrate on nulling out the sight errors, a task for which uncoupled motion capability has shown great promise. This would doubly reduce pilot workload.

A purpose of this effort was to identify aircraft mission segments characterized by high pilot workload that would benefit from 6-DOF application. Because a full scale mission analysis "from the ground up" was not practical, it was determined that the best course of action was to refer to previously developed mission analyses. Five mission analyses (Figure 20) were used as a data base. Each analysis involved unique criteria to determine areas of high workload. In addition, the literature survey and subjective pilot comments aided in identification of high workload mission segments. The following is a list of the mission segments that were common to all of the five analyses.

1. Mission planning/preflight
2. Takeoff/climb out
3. Air-to-air refueling/formation
4. Ingress/egress
5. Target detection and identification
6. Weapon delivery (air-to-ground)
7. Weapon deployment (air-to-air)
8. Loiter rendezvous, cruise
9. Approach/landing
10. Post flight/debriefing

The term, "critical mission segment" (CMS) was used to identify those mission segments that must be successfully completed to ensure overall mission success. A critical mission segment is characterized by one or more of the following:

1) Increased number of discrete activities

2) Time sharing (multiple tasks competing for the pilots' attention) - see Figure 21

3) Intense concentration (nearly undivided attention)

4) Difficult tasks (high level of motor skill required)

5) Severe environmental factors (vibration, wind gusting, etc.)

6) Subjective assessment (pilot identified segments)

Of the initial ten mission segments, the following met one or more of the above criteria and were identified as CMS and showed potential 6-DOF application.

- F-15C MISSION/TASK ANALYSIS
  TIME AND PERFORMANCE FACTORS RATING
- F/A-18 OPERATOR TASK ANALYSIS (ATTACK)
  DIFFICULTY, MODALITY, CRITICALITY, EQUIPMENT LOCATION RATINGS
- F/A-18 TASK ANALYSIS (FIGHTER)
  CRITICALITY, DIFFICULTY, INTERRUPT TIME SPAN
- F/A-18 MISSION ANALYSIS REPORT
  DISCRETE, CONTINUOUS, INTERMITTENT TASKS vs TIME REQUIRED
- LITERATURE SURVEY
- SUBJECTIVE COMMENTS (PILOT INPUTS)
- F/A-18 FUNCTIONAL ALLOCATION (AUTO vs MANUAL)

GP23-0213-24

Figure 20. Survey of Information Sources Used to Determine Critical Mission Segments

1. TERRAIN MONITORING - VISUAL
2. THREAT MONITORING - AUDITORY AND VISUAL
3. ECM DISPENSING - VISUAL/INTELLECTUAL/MOTOR
4. SYSTEMS MONITORING - INTELLECTUAL/VISUAL
5. CONTROL INPUTS - MOTOR/VISUAL

GP23-0213-26

Figure 21. Time Shared Activities

1) Air-to-Air refueling/formation
2) Ingress/egress (possibly TF/TA)
3) Target detection and identification
4) Air-to-Ground weapon delivery
5) Air-to-Air weapon employment
6) Approach and landing

Each of these CMS was analysed in greater detail. The final portion of this study concerns technological considerations of 6-DOF controls and displays as well as necessary control and display symbology.

The first segment to be examined is Air-to-Air refueling/ formation. This CMS requires the performance of gross (large) as well as fine motor skill tasks. Overshoot corrections associated with join-ups and emergency breakaways epitomize the gross motor skill tasks. Fine motor skill tasks are required to maintain relative position. In addition, intense concentration is needed to recognize the necessity for minor position and motion rate corrections. 6-DOF could minimize the number of required motor tasks involved. However, 6-DOF should not be a patchwork fix for inherently poor aircraft handling qualities.

The next CMS having 6-DOF application is ingress/egress. This segment places a myriad of task requirements on the pilot who is subject to a flood of sensory inputs. As a result, the pilot must perform judicious time-sharing to ensure that each input recieves the optimum response. By reducing the required number of motor tasks, 6-DOF can improve TF/TA, help minimize radar cross section, provide a level platform for ECM pods and enhance defensive maneuvers.

Although included in the ingress/egress portion of the analyses, special attention must be given to the task of target detection, identification and designation. High speed, low altitude flight environment reduces the time available for the pilot to visually detect, identify and designate a target. 6-DOF capability could provide the pilot with increased control authority that would reduce the number of required inputs. This would enable the pilot to perform these tasks within the restrictive time limits.

At a superficial level of analysis, Air-to-Ground weapon delivery appears to be another CMS that requires large rapid corrections followed by small, rapid refinements. However, to properly assess the demands on the pilot, the following variables must be considered: 1) type of weapon, 2) delivery mode, 3)delivery tactic, 4) controlling sensor, 5) environment (hostile/ benign; turbulent/calm). Certain combinations of the above variables could result in low pilot workload, while other combinations would require demanding motor skills, mental agility and alertness under high levels of stress. 6-DOF control could reduce workload levels by simplifying the motor tasks and freeing the pilot from time consuming aircraft control maneuvers. In a combat situation, the additional time provided may eliminate the typical requirement to prioritize tasks (e.g., weapon delivery accuracy versus survival). See Figure 22.

The Air-to-Air segment involves tasks and demands common to Air-to-Ground, i.e., steering and tracking, aircraft potisioning and "tracking to solution". Again, many visual and auditory inputs vie for the pilots attention and proper recognition and response is required for successful task completion.

GRAVITY WEAPONS

1. "DUMB" BOMBS EXISTING WEAPON DELIVERY MODES
   - A) CCIP (CONTINUOUSLY COMPUTED IMPACT POINT)
   - B) AUTO RELEASE
   - C) DIVE TOSS
   - D) TCA (TERRAIN CLEARANCE ALTITUDE) RELEASE
2. "DUMB" BOMBS FUTURE WEAPON DELIVERY MODES
   - A) IFWC (INTEGRATED FLIGHT/WEAPONS CONTROL)
   - B) GPS (GLOBAL POSITIONING SYSTEM) BLIND BOMBING
   - C) WAAM (SIDE AREA ANTI-ARMOR MUNITION)
   - D) MAS (MANEUVER ATTACK SYSTEM)
3. SMART BOMBS EXISTING GUIDANCE MODES
   - A) LST (LASER SPOT TRACKING) ILLUMINATING
   - B) RADAR ILLUMINATING
   - C) STV (STEERABLE TELEVISION)
   - D) FLIR (FORWARD LOOKING INFRARED RADAR)

GUNS (STRAFING)

1. CONVENTIONAL MODE
2. IFFC MODE

GUST ALLEVIATION

Notes:

1) All modes require large corrections initially and fine corrections just prior to expenditure
2) All modes will most likely be employed in a hostile environment: SAM, AAA, ECM, enemy aircraft demanding intense concentration and judicious time sharing from the plot.

GP23-0213-28

Figure 22. Weapon Release/Guidance Air-to-Ground
6 DOF Application

The final CMS to be discussed is approach and landing. During this segment the pilot is involved in considerable time-sharing. The pilot must respond to visually presented data from instruments and the external scene as well as auditory stimuli from radio transmission while executing the precise motor tasks associated with landing an aircraft. 6-DOF has the potential to simplify the task of flight path maintenance by reducing the number of required corrections particularly when adjusting for gusting cross winds.

To better understand how 6-DOF could improve operational flying performance, a task analysis was performed on three tasks:, A constant airspeed, 90° heading change; a constant airspeed climb over an object then descend to original altitude and a lateral gust allevation task. The data depicted in Figures 23, 24, and 25 are tallies of subtasks within each task, and are based on a general mission statement, i.e., fighter/attack type aircraft. The three tasks were chosen as a result of the literature survey identifying wings level turn, terrain following/terrain avoidance, and gust allevation as having strong potential for 6-DOF application. Several assumptions are made prior to this analysis. It is assumed that the conventional system and the 6-DOF system provide the pilot comparable precision capability. Also the lateral acceleration effect on the pilot is not taken into account. Control locations and switching operations are very important and are assumed to be optimized in both systems. It is assumed that mental workload associated with estimating lead points is equivalent for roll-out and level-off. Finally, it was assumed that each control input was a separate step. It should be recognized that some inputs can be made simultaneously. This would decrease the number of subtasks shown in the figures but would not effect the final conclusion that 6-DOF control can reduce pilot workload.

60° Bank Turn (Conventional)

1 Move Throttle Forward
2 Deflect Stick Right (Aileron), Start Rolling Moment
3 Deflect Stick Aft (Elevator), as Bank Reaches 60°, gs Increase to 2
4 Neutralize Left/Right Stick Displacement (Aileron), Maintain 60° of Bank, Stop Rolling Moment
5 Estimate Lead Point for Roll Out (Mental)
6 Deflect Stick Left (Aileron), Start Rolling Moment
7 Relax Aft Stick Deflection (Elevator), Decrease gs to 1 Approaching Wings Level
8 Neutralize Left/Right Stick Deflection (Aileron), Stop Rolling Moment
9 Retard Throttle

6-DOF Wings-Level-Turn to the Right *
(Rudder Pedal)

1 Advance Throttle
2 Deflect Rudder Pedal Right, Start and Maintain Turn Rate
3 Estimate Lead Point for "Roll Out"
4 Neutralize Rudder Pedal, Stop Turn Rate
5 Retard Throttle

- **4 Fewer Subtasks (44% Reduction) Required to Complete the Task**

*Note: 6-DOF mode active

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Figure 23. Constant Airspeed Turn

Conventional

1 Advance Throttle
2 Deflect Stick Aft (Elevator), Start Climb
3 Neutralize Aft Stick Deflection (Elevator) to Maintain Climb Rate
4 Estimate Lead Point
5 Deflect Stick Forward (Elevator)
6 Neutralize Stick Deflection to Level Off
7 Deflect Stick Forward (Elevator) to Start Descent
8 Reduce Throttle
9 Neutralize Stick Deflection to Maintain Descent Rate
10 Estimate Lead Point
11 Deflect Stick Aft (Elevator) to Start Level Off
12 Neutralize Stick Deflection to Level Off
13 Advance Throttle

6-DOF Vertical Path Control Mode*

1 Advance Throttle
2 Deflect Control to Start and Maintain Climb
3 Estimate Estimate Lead Point for Level Off
4 Neutralize Control to Stop Climb and Level Off
5 Deflect Control to Start and Maintain Descent
6 Reduce Throttle
7 Estimate Lead Point for Level Off
8 Neutralize Control to Level Off
9 Advance Throttle

- **4 Fewer Subtasks (31% Reduction) Required to Complete the Task.**

* Note: 6-DOF mode active

GP43-0089-177

Figure 24. Constant Airspeed Climb Over an Object Then Descend to Original Altitude

Conventional

1 Advance Throttle
2 Deflect Stick Right (Aileron) to Start Rolling Moment
3 Deflect Stick Aft (Elevator) to Maintain Altitude
4 Neutralize Left/Right Stick Deflection (Aileron) to Stop Rolling Moment
5 Estimate Lead Point
6 Deflect Stick Left (Aileron) to Start Rolling Moment, Rolling Through Wings Level
7 Relax Aft Stick Deflection (Elevator) as Bank Approaches 0°
8 Deflect Stick Aft (Elevator) as Bank Increases
9 Neutralize Left/Right Stick Deflection (Aileron) to Stop Rolling Moment
10 Estimate Lead Point
11 Deflect Stick Right (Aileron) Start Rolling Moment
12 Relax Aft Stick Deflection (Elevator) as Bank Approaches 0°
13 Neutralize Left/Right Stick Deflection (Aileron) to Stop Rolling Moment
14 Retard Throttle

6-DOF Lateral Translation Mode*

1 Advance Throttle
2 Deflect Control to Start and Maintain Translation
3 Estimate Lead Point
4 Relax Control to Stop Translation
5 Retard Throttle

- **9 Fewer Subtasks (64% Reduction) Required to Complete the Task.**

*Note: 6-DOF mode active

GP43-0089-178

Figure 25. Gust Alleviation, Ground Track Maintenance at Constant Airspeed

In the constant airspeed turn to heading task, four fewer subtasks are required to complete the task when using uncoupled flight - a reduction of 44%. The flight path maintenance task, associated with TF/TA or glide slope maintenance (landing task) indicated four fewer subtasks or a 31% reduction when using uncoupled flight. A significant reduction of subtasks required to alleviate gust effects results when uncoupled flight is applied. A total of nine fewer subtasks (64% reduction) is required for ground track maintenance associated with strafing or line-up with the runway.

The purpose of this analysis was to determine whether 6-DOF technology could reduce the number of subtasks required to perform certain tasks. This appears to be the case.

6-DOF application toward workload reduction must be considered in the context of existing and evolving technologies. Further study of the application of 6-DOF Should include analysis to determine: 1) the optimum degree of automation, 2) proper controls and displays, 3) the suitability of moding.

2. CONTROLLER DESIGN CONSIDERATIONS - Several areas of controller design must be addressed to reduce the impact of six-degree-of-freedom control on pilot psychomotor and cognitive workload. The methods of crew systems design developed in Reference 65 are a good starting point. With manual control of uncoupled aircraft motion, there are several issues which must be addressed.

As discussed in the literature survey, there exists a large literature base concerning the use of hand controllers in applications ranging from simple laboratory tracking studies to flight tests. In spite of four decades of research, the fundamental characteristics of "good" or "optimum" controller design continue to elude us. This is partially due to the empirical and/or "applied" nature of much past research, and the basic biomechanical complexity of the interface between the pilot's limbs and the controller's mechanical characteristics. Although it is not practical to attempt to develop the fundamental principals of controller design on this project, we should take into account the various controller design factors that are known to influence manual control system performance, and also if possible provide experimental scenarios that provide a sensitive test of these factors. The various factors include physical dimensions, force-feel characteristics and their relationship to the vehicle modes and display variables being controlled. A summary of the various factors follow.

Anthropometric Layout

The controller physical dimensions and arrangement should of course be consistent with the pilots seating posture and controller placement. Some basic cockpit layout specifications are given in Ref. 65. Sidesticks provide more restrictive design requirements, however, including appropriate arrangement of an armrest. Staten and Theurer (Ref. 21) suggest appropriate lateral and longitudinal neutral controller positions, and armrest adjustment to accommodate pilot hand size and garment bulk. Vertical seat adjustment is apparently adequate to accommodate pilot size. Finally, armrest angle in the horizontal plane should be set to permit the pilot's elbow to be as close to his side as possible.

Force Feel, Displacement and Stick Gain

Experience with the F-16 suggests that isometric sticks are less than desirable in the operational environment. Stick movement allows mechanical stops to indicate to the pilot the limits of stick effectiveness. Stick movement also can be arranged to provide mechanical filtering of disturbances as implied by the results and analysis of Refs. 13 and 14. In fact, it is possible that there is an optimum controller mechanical impedance that interacts with limb biomechanical characteristics to minimize force disturbances while still allowing adequate controller response. The NT-33 controller experiments as summarized in Ref. 23 are probably adequate to specify controller-to-displacement characteristics.

The need for active force feedback or cuing systems is still an open issue. These systems definitely can improve operator performance by giving immediate kinesthetic feedback on the consequences of controller inputs, and can be used to indicate trim status. However, an active force feedback system implies greater complexity then a simple passive fly-by-wire stick. Also, to the extent that a fly-by-wire system is set up as a command system, there is some direct correspondence between stick force and commanded variables such as vertical "g". One disadvantage of passive stick feel system is the inability to sense control system/surface limits which will vary with trim conditions.

Stick gain is usually specified operationally in terms of force to a given vehicle motion variable. Gains will be dependent on CCV mode, but little attention has been paid to optimum gains or gain scheduling for unconventional modes. Gain can have a rather broad optimum in manual control studies, and preference for higher gains usually accompanies training. Typically gain is less sensitive around null, and increases by some factor for larger force levels to accommodate large slewing commands or control against large disturbances. These characteristics will have to be worked out empirically, and perhaps should be set to preferred levels for each pilot subject.

Harmonization

Harmonization refers to the variation in force feel characteristics between control axes. For hand controller control of conventional and CCV modes we have the standard lateral and longitudinal axes in addition to controllers for the unconventional modes. There seems to be general consensus about having stiffer pitch control than roll control, with the differences in gradients on the order of a factor of three (apparently the reverse is true of the Space Shuttle controller which has not proven to be very desirable).

Actuation forces for stick-mounted switches should be appreciably lower than typical handle forces to avoid inadvertent control of the conventional modes. Details are lacking, however, between the specific harmonization between continuous control switches and handle forces. Also, for a two axes switch it is not clear whether gradients in each axis should differ. Judging from the Ref. 22 finding on the poor directional control of the thumb, perhaps different gradients would be helpful.

Control/Display Relationships

Past research has shown that the relative display symbol motion to controller inputs should be direct. Fixed-base research has also shown that special display symbols are helpful in indicating the direction of controller inputs (Refs. 6, 22). In a moving-base environment, these cues may be redundant, however. Display formats and symbology should be carefully considered so that performance with CCV modes is not penalized by lack of appropriate display information.

The display requirements for uncoupled six-degree-of-freedom motion may be critical to the effective operational utility of these modes. In discussions with the AFTI/F-16 pilots, two specific areas of need were identified: Some form of indication of the saturation of a control mode and an indication of the energy state (energy management). Energy state feedback is vital when modes of motion develop high drag. The saturation warning is especially important when fixed electrical force sensing controls are used since there is no motion to indicate the limits of control. The energy management display is a complex issue involving not only uncoupled control, but the more conventional controls as well. This topic is not within the scope of the current effort. Suffice it to say that initially pilots will be unfamiliar with the amount of drag generated by actuation of an uncoupled control mode.

Display strategy and symbology for 6-DOF application will be critical for 6-DOF operation (see Figure 26). Candidate displays must also provide usable status and performance indications. Energy management, control saturation or remaining authority as well as the standard performance indicators of airspeed, altitude, alpha, beta, etc., will be considered. Additional control symbology for HUD and/or helmet mounted sights/displays (HMS/D) must be developed to provide the pilot with unambiguous feedback of aircraft performance. Specific modes such as Air-to-Air, Air-to-Ground, ECM And Navigation may require unique and possibly innovative display subjects. Feedback, via displayed symbology, of the 6-DOF control mode activated must be provided to the pilot.

I ***PERFORMANCE INDICATIONS***

A) ENERGY MANAGEMENT

B) PERFORMANCE DATA

- AIRSPEED/MACH NUMBER
- RADAR AND BAROMETRIC ALTITUDE
- VERTICAL AND LATERAL VELOCITY
- ENGINE INSTRUMENTS

II ***CONTROL INDICATIONS***

A) VELOCITY VECTOR (VERTICAL AND LATERAL - POTENTIALLY OFF HUD)

B) ATTITUDE (PITCH, ROLL, POINTING)

C) ACTIVATED DEGREES-OF-FREEDOM

- WLT
- VERTICAL TRANS
- LATERAL TRANS
- M.E.
- VERTICAL PATH CONTROL
- POINTING

D) CONTROL SATURATION/REMAINING OR AVAILABLE AUTHORITY

E) Gx, Gy INDICATION

F) STALL WARNING

G) ENGINE LIMITS DATA (α AND β AT ENGINE INLETS)

H) WATERLINE SYMBOL (REPLACES VELOCITY VECTOR WHEN VEL VECT IS OFF HUD)

I) TURNING RATE

- COORDINATED FLIGHT
- WINGS LEVEL TURN

III ***MODES (DISPLAY)***

A) COMBAT

- AIR-TO-AIR
- AIR-TO-GROUND
- ECM

B) NAVIGATION

C) STORES MANAGEMENT

Notes:

- ECM displays will most likely be superimposed on air-to-air and air-to-ground displays
- Activated degrees-of-freedom may depend on
  1) Combat mode selection (e.g., air-to-air, air-to-ground)
  2) Weapon system in use (i.e., dumb bombs, smart bombs, guns, etc)
  3) Degree of automation (i.e., IFFC, IFWC, etc)

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Figure 26. Candidate Display Requirements Associated With 6-DOF Technology

While physical and visual cues can provide much of this information, it is important to remember that pilots will be initially unfamiliar with uncoupled motion capabilities and their physical manifestations in terms of lateral acceleration and velocity. Some of the elements listed above will only be needed when a specific mode is engaged. The multi-mode control structure would allow the proper display to be presented to the pilot depending on the mode selected. The symbology and format required by these displays are sensitive and complex to determine and are beyond the range of this study.

3. MEASUREMENT METHODS - In the previous sections we have reviewed past experimental efforts and examined possible advantages of uncoupled aircraft motion. We have also examined design considerations which may impact the effectiveness of uncoupled motion control. A remaining area which needs to be addressed is how to measure the control effectiveness. In this section, using examples from and knowledge gained during the literature review, we will examine methods of measuring the effectiveness of controller implementations both in terms of performance and pilot workload. It may not be practical or even desirable to implement all of the suggestions in a single experiment. Rather, the methods suggested should be considered a guide to possible evaluation techniques.

The effect of controller design variables on pilot performance can depend strongly on task variables and the sensitivity of performance measures. The term "performance measures" is used here in the broadest context to include measures of system performance (e.g., tracking error, hit probability, etc.), pilot behavior (e.g., response functions, stick activity) and pilot opinion ratings. Because of the pilot's adaptive properties, he can often compensate for changes over a wide range of system variables to maintain relatively constant system performance, and the consequences of non-optimum conditions may only be represented in objective behavioral measures and/or subjective ratings.

By "task" we mean some portion of a mission segment where the pilot's performance objective is well defined, and pilot-vehicle responses are stable enough to permit reliable and meaningful performance measurements. The HQDT task (Ref. 47) is an example of a stable, well defined task. The terminal phase of air-to-ground attack, landing approach, and air-to-air refueling are additional examples that represent other flight conditions and/or performance objectives.

In order to achieve reliable sensitivity measures, we must control the forcing functions that provide command inputs or disturbances to the system. Figure 27 provides a conceptual system model for providing forcing functions and measurements that focuses on the pilot's controller actions. Based on displayed information, the pilot exerts forces on the controller, which responds according to the biomechanical transfer function Y_{ff} to generate controller actions δ, which are input to the vehicle dynamics. The control signal provides one point where a disturbance signal, δ_d, can be provided to simulate turbulence while providing a simple measure of control effectiveness, the control error function δ_e. Also, for single point control loops, the describing function between δ_e and δ_d can be used to determine basic pilot response behavior (this approach is developed for automobile steering tasks in Refs. 9 and 66).

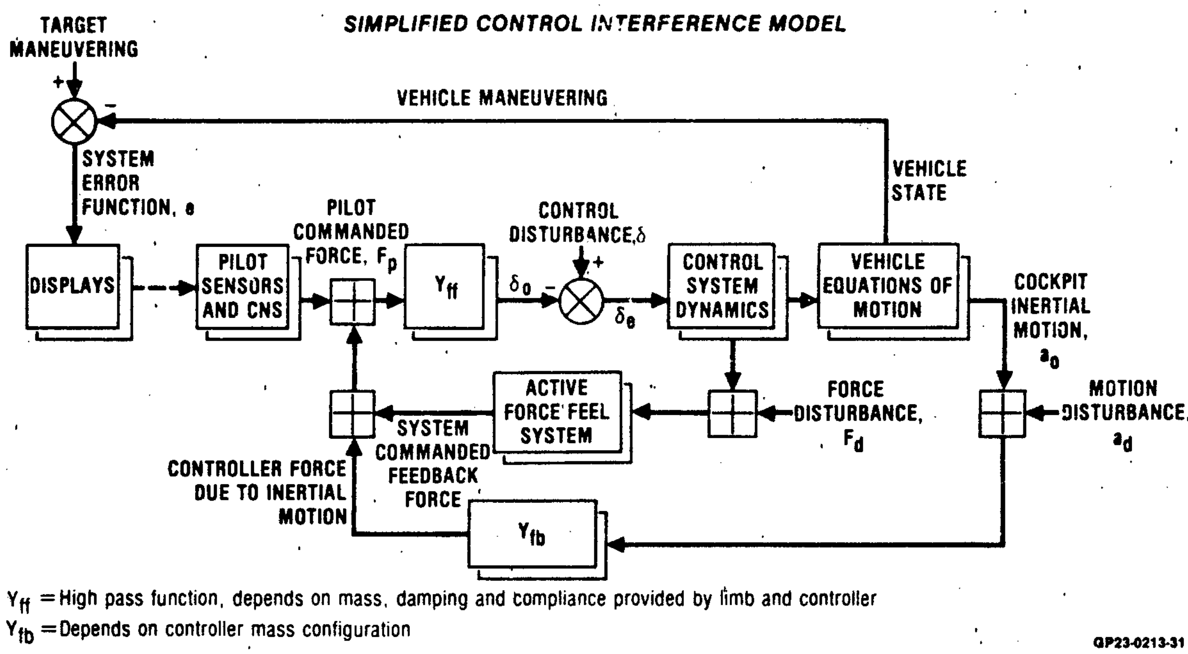

Figure 27. Conceptual Block Diagram for Task Inputs and Measurement Variables

The control dynamics and vehicle equations of motion then develop visual display and motion output. The visual display quantity might be referenced to a maneuvering target which provides a system command input. System errors with respect to targets or other references (e.g., a landing beam, refueling probe, etc.) provide a measure of overall system performance, and describing functions can be obtained to measure the ability of the pilot/vehicle system to follow command inputs.

Vehicle motions can couple back into the control loop by inertially disturbing the limb controller system through the biomechanical transfer function Y_{fb}. Under adverse conditions this coupling can lead to PIO's. A disturbance can be injected into this loop (a_d) to measure the motion coupling dynamics. The difference between motion and control disturbances (a_d and δ_d respectively) is that δ_d results in direct visual feedback without pilot control action, whereas a_d does not.

If an active controller force feedback system is provided, then a force disturbance (F_d) can also be provided as illustrated in Figure 27. The purpose of F_d inputs would be to measure the limb controller response dynamics associated with kinesthetic cues. The measurements would be useful in studying the effects of variations in controller impedance (i.e., inertia, compliance and damping). The action of the force disturbance, F_d, differs from the motion disturbance, a_d, in that the basic force loop closure does not involve the vehicle dynamics.

The Figure 27 block diagram represents a simplified, single control point system. For specific tasks and modes the appropriate block diagram must be developed. For multi-control point tasks (e.g., conventional plus direct force modes), the vehicle state and motion outer loops are still the same but provisions must be made for considering multiple control actions.

If properly designed, more than one forcing function input can be used at the same time. For measurement sensitivity, inputs should be line spectra with random phasing, and with all spectral components orthogonal over the measurement period. This basically amounts to sum of sine wave forcing function inputs with random phasing between the components, and an integer number of cycles per run length.

The frequency range for each input will differ depending on the basic dynamics of the given loop closure. For example, the outer loop closure for following maneuvering targets probably has a bandwidth of less than 1 rad/sec, so the target maneuvering forcing function would have frequencies spacing the range from 0.2 to 2 rad/sec. The lowest frequency implies a run length of about thirty seconds in order to meet the orthogonality condition. Table 1 summarizes the approximate frequency range of interest for each of the Figure 27 inputs.

TABLE 1. INPUT FREQUENCY RANGES AND MEASUREMENT RUN LENGTH

Input Forcing Function	Closed Loop Bandwidth (rad/sec)	Measurement Frequency Range (rad/sec)	Run Length (sec)
Target Maneuvering	1	0.2 - 8	30
Control Disturbance	2 - 5	0.5 - 10	12
Motion Disturbance	5	1 - 10	6
Force Disturbance	10	2 - 30	3

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Given the above inputs and Fast Fourier Transform (FFT) capability, we can then measure the dynamic response functions for each loop at the forcing function frequencies. Also we can obtain remnant measurements at spectral components in between. The dynamic response functions will give an indication of loop closure bandwidths for various controller/mode combinations. The remnant measure will give some indication of the pilot's control precision, and the degree of disturbance caused by the motion environment.

The above FFT analysis will provide pilot behavioral measures of control precision and bandwidth. More traditional mean square error measures can be obtained to quantify system performance. These objective measures should also be supplemented with pilot subjective ratings of task difficulty and workload as discussed in the next section.

Example Task - In this section we will take as an example a specific task and analyze it to determine requirements for pilot psychomotor and cognitive behavior, workload demands and appropriate measurements. The example task is an air-to-ground attack using conventional weapons which can be subdivided into five distinct phases as follows:

- Approach - Set up maneuver relative to target, establish trim and power settings; select appropriate control and display modes.
- Curvilinear Tracking - Roll in to curved approach path; arm weapon for release.
- Transition - Increase roll angle (> 90 deg) and pull nose down to run-in line; roll out and establish straight run-in dive.
- Straight Tracking - Null out sight errors, release weapon.
- Pull-Out - After weapon clearance, establish high g pull up.

The air-to-ground weapon delivery task requires both psychomotor and cognitive pilot behavior. Psychomotor behavior refers to controlling aircraft attitude, path, and speed. Cognitive behavior refers to the pilots supervisory role is setting up the maneuver, monitoring aircraft status aside from the specific control task, and the estimation and decision making required to weapon release. The pilot's workload associated with psychomotor and cognitive tasks will be highly dependent on the handling qualities of the aircraft modes used, and the sophistication of the fire control system and weapon delivery display format. For our discussion here, we will assume some nominal display format and focus on the controller and aircraft modes which are the central issue on this project.

Now let us consider some of the detailed task elements in the above maneuver phases that define required pilot behavior and workload demands.

1. Approach

In the approach phase, the demands on the pilot are primarily procedural. Following a predetermined checklist, the pilot selects modes and establishes settings for an air-to-ground attack. Workload is probably not very high here, but under actual combat conditions there is probably a reasonable anxiety level.

2. Curvilinear Tracking

During the curvilinear tracking phase, the pilot is holding a coordinated turn at constant altitude. The psychomotor tasks consist of compensatory tracking including holding a constant bank angle and zero rate of climb throughout the turn. Cognitive workload is encountered mainly in general monitoring of the tactical situation and aircraft state, continuing checklist procedures such as weapon arming, and processing target heading to determine the timing of the transition phase (i.e., estimation and decision making).

3. Transition

The transition phase consists primarily of a transient precognitive tracking maneuver initiated by the pilot at the appropriate time to transit from a coordinated turn to the straight-line run-in dive required for weapons release. The transient maneuver involves increasing roll angle to approximately 120 deg and pulling the nose down to the run-in line, followed by roll-out into a straight line dive. Well learned precognitive maneuvers do not involve much psychomotor workload once triggered. The primary cognitive workload is encountered in monitoring and timing the roll out so that the aircraft is lined up with the run-in line heading.

4. Straight Tracking

This segment involves compensatory tracking of the bombsight display. Since accuracy is critical, psychomotor workload is high. Cognitive workload is high as well because the pilot is continually estimating and predicting the weapon release timing.

5. Pull-Out

Following weapon release command, the pilot waits for some short interval to guarantee weapon clearance then initiates a high-g pullup. This is initially a precognitive transient tracking maneuver, followed by maintaining a constant, safe g level until a desired rate of climb is established to regain altitude for additional go-arounds or return to base. Psychomotor and cognitive workload are low during this phase.

Workload and Performance Measures - In Figure 2?, a hypothetical time line of pilot psychomotor and cognitive workload is illustrated. It should be kept in mind that the absolute workload levels and relative changes from phase to phase can be a sensitive function of vehicle handling qualities, fire control system computations, and display format. The issue we wish to focus on here are performance and workload changes due to different controller configurations and flight modes. (Figure 28 reproduces an earlier Figure for the reader's convenience.)

Figure 28 provides a convenient means for establishing appropriate objective and subjective performance measures. The timeline indicates that there are two segments of limited time duration where steady-state response measures can be obtained. Aileron control (δ_a) and motion disturbances could be introduced during the curvilinear tracking segment to simulate turbulence. This would then allow measures of lateral-directional control performance. During the straightline dive segment, disturbances could be applied to vehicle path which would allow performance measures of path control. During the transition segment, transient measures could be developed to quantify how accurately the pilot rolls out to the correct target heading and depression angle.

Several different categories of pilot subjective opinion can be solicited for this task. First, note that the straight tracking segment of air-to-ground attack is the most amenable to improvement with CCV mode capabilities. As has been noted in the past (e.g., Hoh, Ref. 26) direct side-force control would help eliminate the "pendulum effect" in bombsight control. Thus, psychomotor workload would potentially be reduced during straight tracking through the use of direct side force control.

In order to measure the above advantage of direct side-force control, we would like to focus the pilot's attention on the straight tracking segment. Several categories of subjective opinion can then be obtained. The first is to obtain standard Cooper-Harper ratings relative to some performance criterion. This procedure should be familiar to most pilots and would allow tie-in with other aircraft studies. A second rating could focus on "attentional demand" in an attempt to more directly measure workload independent of whether performance objectives are met or not. This scale could range from "minimal" to "excessive" attentional demands.

A third means of obtaining pilot subjective opinion would involve relative ranking of several experimental conditions. This method would be particularly useful for rating several conditions experienced in the same experimental session. Finally, pilot free-form comments should be obtained that are focused on task, controller and control mode characteristics. These comments would be obtained in debriefings at the end of runs, sessions, and the entire experiment.

	APPROACH	CURVILINEAR TRACKING	TRANSITION	STRAIGHT TRACKING	PULL-OUT
PSYCHOMOTOR TASKS	COMPENSATORY: ● STABILIZE ATTITUDE ● MAINTAIN ALTITUDE	PRECOGNITIVE: ● ROLL INTO TURN COMPENSATORY: ● HOLD BANK ANGLE ● MAINTAIN ALTITUDE	PRECOGNITIVE: ● ROLL TO ~ 120° ● PULL DOWN TO RUN-IN LINE ● ROLL OUT IN DIVE	COMPENSATORY: ● NULL OUT SIGHT ERRORS	PRECOGNITIVE: ● PULL UP @ HI g COMPENSATORY ● MAINTAIN CLIMB RATE TO DESIRED ALTITUDE
PROCEDURAL AND COGNITIVE TASKS	● FOLLOW CHECKLIST ● MODE SELECTION ● MONITOR TACTICAL SITUATION ● MONITOR AIRCRAFT STATE	● CONT CHECKLIST ● ARM WEAPON ● CONT MONITORING TACTICAL AND AIRCRAFT STATE ● ESTIMATE TIMING OF TRANSITION	● ESTIMATE TIMING. OF ROLL OUT TO TARGET HEADING	● ESTIMATE WEAPON RELEASE TIMING	● MONITOR TACTICAL SITUATION ● MONITOR AIRCRAFT STATE

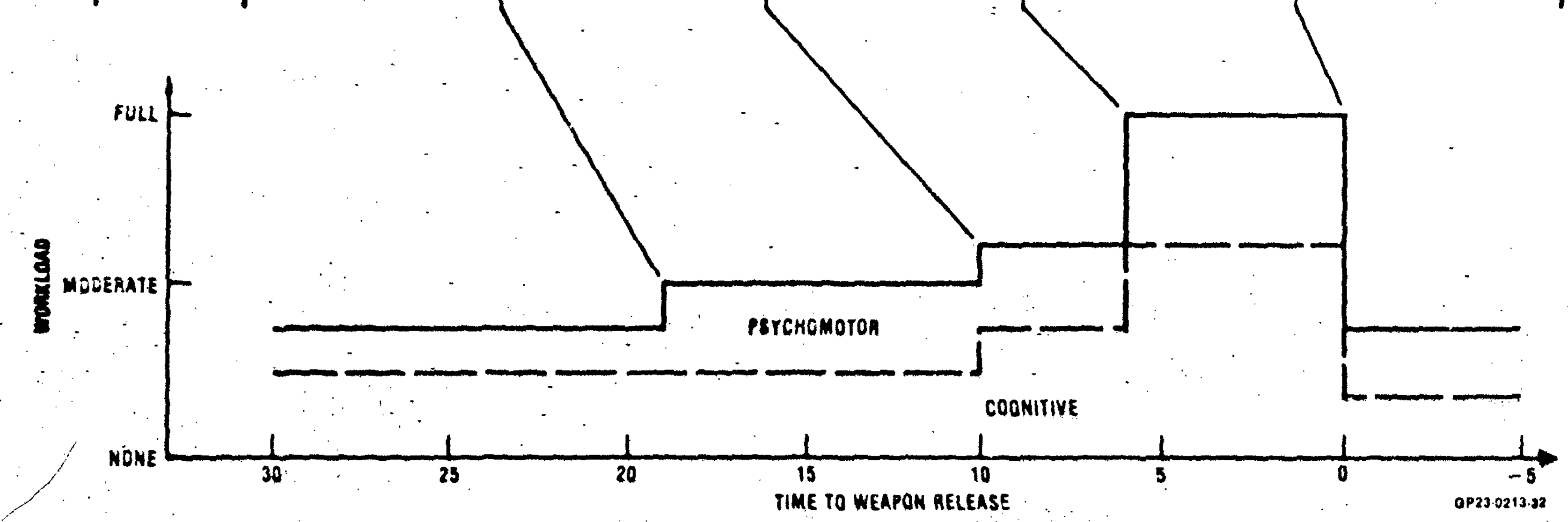

Figure 28. Task Analysis for Air-to-Ground Weapon Delivery

SECTION IV
CONTROLLERS FOR UNCOUPLED MOTION SIMULATION

The objective of this simulation was to gather additional substantiating data in order to develop design criteria for cockpit control devices for uncoupled aircraft motion. Based on the extensive review of manual control and uncoupled aircraft motion carried out in Phase I of this study and on comments and suggestions from pilots and engineers within the industry, the basic issues addressed by this simulation were the following:

- o Use of additional controllers mounted on the "Conventional" flight path controller as opposed to remote or separate controllers
- o Effects of tasks on uncoupled motion controller characteristics
- o Interaction of conventional flight path controllers characteristics and the uncoupled motion controllers
- o Influence of motion disturbances on the pilot-aircraft interfaces
- o Use of thumb and finger isometric controllers as single axis devices rather than as dual axis controllers.

For this simulation, these issues were to be addressed using methods identified in the literature. These analysis tools included task performance scores, frequency analysis, workload assessment, and pilot subjective ratings for a number of different controllers in a variety of environments.

1. STUDY PLAN CONSIDERATIONS - Taken in their broadest context, the objectives outlined above result in an almost infinite test matrix of modes, controllers, and tasks. The knowledge and experienced gained during Phase I of this effort was used to determine those areas of greatest interest. This knowledge, combined with the normal constraints of time and resources, served to reduce the matrix to a tractable form.

The reduction began first by examining the modes found useful in the literature. These include longitudinal and lateral modes such as:

Longitudinal Modes

- o Vertical Path Control (VPC) - Normal load factor control at constant angle of attack
- o Vertical Translation (VT) - Vertical acceleration/velocity control at constant aircraft attitude
- o Fuselage Elevation Aiming (FEA) - Fuselage angle of attack control at constant load factor

- Drag Modulation (DM) - Velocity control at constant thrust setting

- Maneuver Enhancement (ME) - Blending of conventional and uncoupled responses to provide quicker response and/or improved ride qualities

Lateral Modes

- Wings Level Turn (WLT) - Heading control with no sideslip or roll attitude change

- Lateral Translation (LT) - Lateral acceleration/velocity control without yaw rotation or roll motion

- Fuselage Azimuth Aiming (FAA) - Azimuth angle control with no lateral load factor.

After reviewing this list, drag modulation and maneuver enhancement were eliminated from consideration for the simulation. Maneuver enhancement usually combines conventional and uncoupled response on a normal flight controller. Specification of controller requirements for this mode are probably best covered by the existing conventional sections of the MIL-STANDARD. Drag modulation is a mode which may be very useful; however, it does not lend itself to flying qualities evaluation using the same tasks and methods as the other uncoupled modes. These modes should be examined in a future effort.

When reviewing the literature, it becomes apparent that when longitudinal and lateral uncoupled modes are examined simultaneously, the lateral modes stand out as having the greatest potential application. The longitudinal axis of an airplane is by far the most powerful axis. It is used to change the aircraft pitch attitude and aircraft altitude. It is also the prime motivator in changing aircraft heading. However, using the longitudinal axis to change heading first requires that the aircraft be rolled to put the lift vector in the necessary orientation. If a constant altitude is desired (i.e., a level heading change), then the pilot must blend longitudinal control force with aircraft roll attitude. Estimation of the proper lead is also necessary to ensure that the aircraft can be stopped (i.e., rolled out) on the desired heading.

The lateral uncoupled modes provide the pilot with a means of controlling aircraft fuselage heading and flight path direction, separately or combined, by manipulation of one device in the cockpit. This greatly simplifies the pilot heading control over the range of authority available.

For this reason, it was decided to limit this simulation primarily to investigation of controllers for the lateral modes. A limited evaluation of controllers for vertical translation in an approach and landing task was conducted, however. The use of vertical translation in this task had shown potential benefit for control of touchdown dispersion in precision landing tasks.

The next simplification was made by a decision to concentrate on Class IV aircraft and tasks. This was felt to cover the widest range of uncoupled motion application, including weapon delivery, while also covering the area where uncoupled motion would be useful for other aircraft, i.e., approach and landing. Two tasks were considered which would be applicable to other class aircraft. These included terrain following/terrain avoidance and low altitude parachute extraction of cargo from airlift craft. While interesting, it was felt that these tasks would be best left to future specialized efforts.

The remaining area of the simulation test plan to be considered included exactly what controllers to examine and what characteristics to consider. Seven basic considerations of aircraft controller design were identified in the literature review. These included:

(1) Force-displacement characteristics - The amount of displacement for a given force, (e.g., nonlinear gradients, breakout forces, force limits)

(2) Force feedback and trim cuing - Control system and surface forces reflected at the controller (e.g., parallel vs. series trim systems, stick shakers, motion stops)

(3) Harmonization - The relative force-displacement characteristics between control axes (e.g., lateral versus longitudinal stick force levels)

(4) Controller input - aircraft response characteristics - The amount of aircraft response (pitch rate, normal acceleration, etc.) for a given input to the controller by the pilot (force or deflection).

(5) Motion coupling and disturbance - Aircraft motions which inertially couple into control axes or interfere with the pilot's control manipulation (e.g., bobweight effects producing control cues and commands)

(6) Controller/display relationship - The relationship between controller actions and display response (e.g., controller logic versus outside-in or inside-out display)

(7) Static anthropometric controller characteristics - The physical size and location of the manipulator with respect to the pilot (e.g., circumference of the controller compared with the pilot's hand size).

The first four of these areas are dependent on some knowledge of the input-output relationships that are acceptable to the pilot. These include the mechanical controller characteristics of breakout force and force-deflection, as well as pilot input/aircraft response relationships of deadband and maneuver gradient. The maneuver gradient is defined as the ratio of the change in pilot input to the change in aircraft response. Without knowledge of the preferred input-output relationships and the maximum authority required for the task, the designer has little idea of what range of force and displacement characteristics are required for his design.

There are an infinite number of combinations of maneuver gradient and uncoupled mode authorities which could be examined, particularly if dual gradients are considered. With dual force-deflection and/or maneuver gradients, it is necessary to define the breakpoint and degree of slope change. In order to determine these characteristics, the designer must have some knowledge of the preferred gradients for fine tracking to define the inner slopes. In addition, he must know at what authority level to change from a tracking gradient to a steeper acquisition gradient. Since there are no clear definitions of even the simplest linear gradients for uncoupled mode control, it was decided to concentrate on linear gradients for this simulation.

The fifth consideration on this list, motion coupling and disturbance, was addressed during the simulation. The mechanization and results of these studies are presented in the spectral analysis. Items (6) and (7) were not experimental variables in this simulation. However, pilot comments and suggestions were collected on the head up display (HUD) format and controller size, shape, and location in the cockpit.

The selection of controllers for the simulation was based on devices identified in the literature survey and on availability and time constraints. It is felt that the controllers chosen represent a cross section of previous experience and recent developments in controller hardware. In keeping with current trends in aircraft control system and cockpit design, a sidestick controller was chosen as the primary conventional response controller. The controller is similar to those used in recent, advanced helicopter simulations (References 56 and 71) and incorporates two additional control axes. The sidestick can be twisted about its vertical axis or heave inputs can be made by applying forces along the vertical axis. The sidestick also has a thumb operated miniature joystick, mounted on top of the stick grip, which provides additional control input capability. Other controllers used in the simulation included rudder pedals, a thumbwheel operated by the pilot's left hand, and a twist throttle similar to the one used on the AFTI/F-16 (Reference 51). A detailed description of these controllers appears in Section 3.

The controller characteristics which were examined are shown in Figure 29. For the rudder pedals, both the force-deflection and input-output relationships were varied. For the remaining controllers, the force-deflection characteristics were fixed and the input-output relationships were varied.

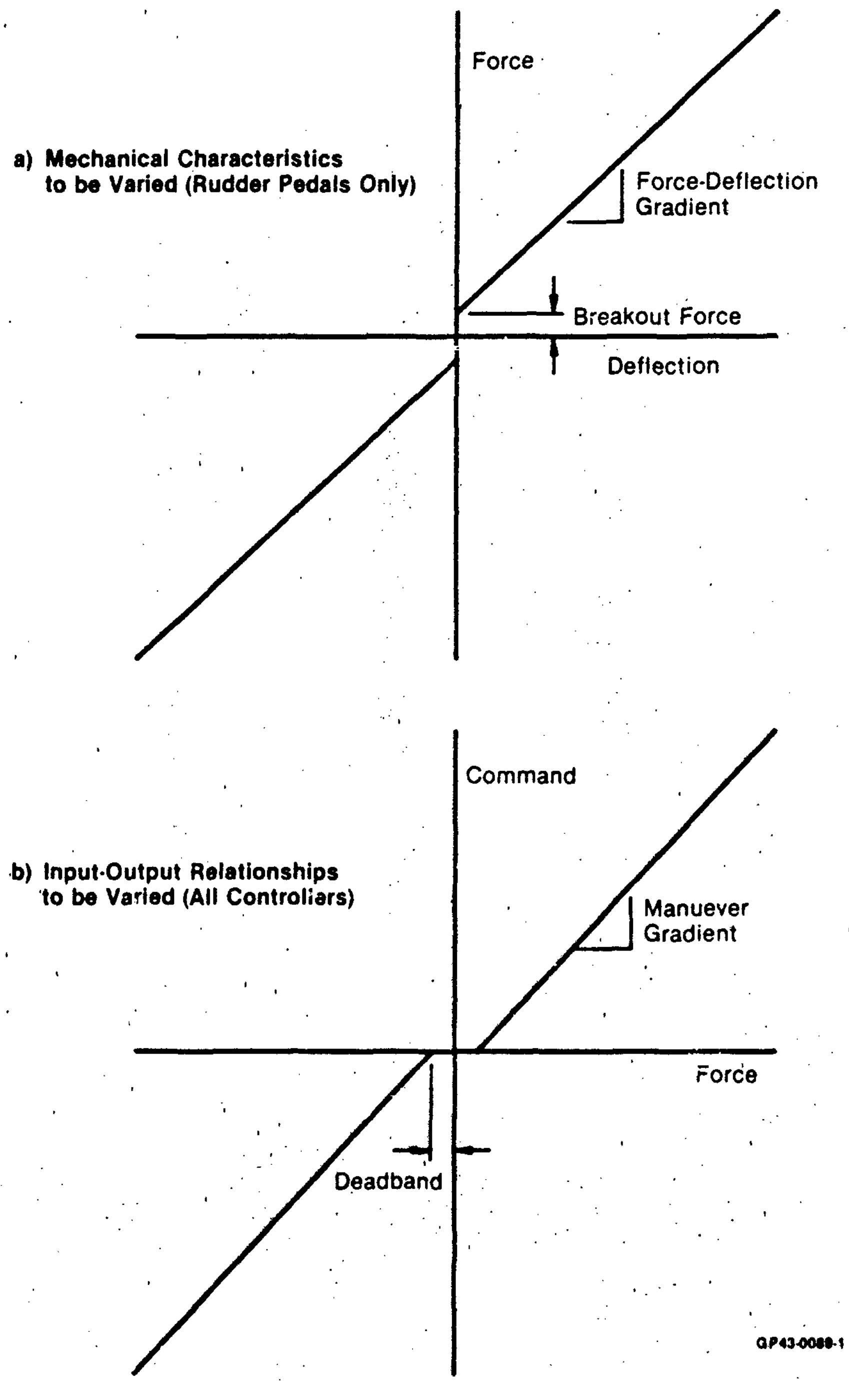

Figure 29. Controller Characteristics to be Examined

2. SIMULATOR DESCRIPTION - The simulation was conducted on the Large Amplitude Multimode Aerospace Research Simulator (LAMARS) at Wright-Patterson AFB, Dayton, Ohio. LAMARS, shown in Figure 30, consists of a five-degree-of-freedom beam-type motion system which carries a single-place cockpit enclosed by a spherical display dome on the end of a 30 foot beam.

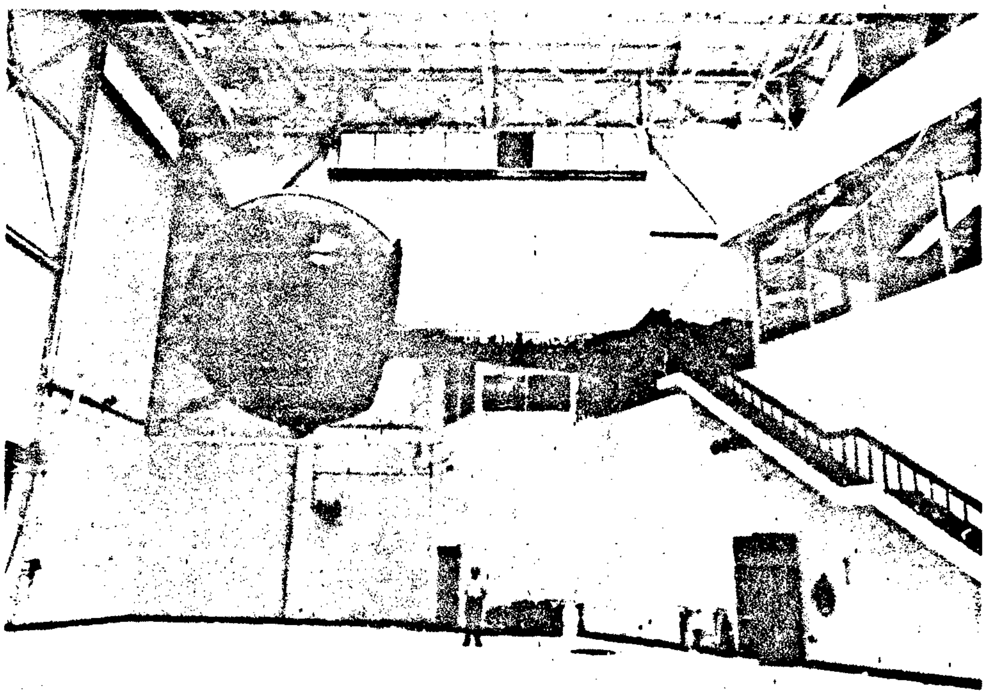

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Figure 30. LAMARS Motion-Base Simulator

The visual display system uses the inside of the 20 foot diameter dome as a wide angle spherical projection screen. A sky-earth projector and a target projector provide the pilot with a visual representation of the outside environment. The display provides a 266° field-of-view in the horizontal plane and 108° in the vertical plane for the sky-earth presentation. A terrain board system was used to project a 45° wide by 36° hightly detailed terrain image for simulation tasks at low altitude. The cockpit design is compatible with all modern fighter aircraft configurations and can be readily adapted to different configurations.

The motion system is used to provide onset cues at the pilot station in proportion to those experienced in actual flight. For this simulation the onset vertical accelerations experienced by the pilot were 0.15 of those that would be experienced in flight. The lateral accelerations were scaled by a factor of 0.1. Beam lateral and vertical travel is limited to ± 10 feet with instantaneous acceleration limits of ±3 g's vertically and ±25 degrees. Maximum angular acceleration are ±400, ±460, and ±200 degrees per second in pitch, roll, and yaw, respectively. Washout filters are used to maintain actual simulator motion within these limits. Additional dynamics due to the simulator are not clearly defined at this time and were not accounted for in the results derived from this simulation.

The air-to-ground weapon delivery and approach and landing tasks utilized the terrain board system. This system consists of two illuminated three-dimensional terrain models. Each model is equipped with its own gantry-supported, optical-probe equipped television camera positioned by computer controlled servos. Each model, mounted vertically, is 15 feet high by 47 feet long and includes scale models of hills, deserts, rivers, lakes, and urban and rural terrain. One model represents an area 11 by 36 nautical miles (1:5000 scale). The other model represents a subsection of the 1:5000 board which is 3 by 11 nautical miles (1:1500 scale). The area duplicated on the two boards includes an airport complex complete with strobe and approach lights, airport traffic control lights, and full category II lighting. The viewing area is continuous in heading and roll but limited to 24 degrees nose up and 47 degrees nose down in pitch. The maximum angular accelerations are 300 degrees per second squared in pitch and yaw and 500 degrees per second squared in roll.

3. <u>CONTROLLERS</u> - The general cockpit layout is shown in Figure 31. The controllers examined during this simulation included rudder pedals, a 4-axis sidestick controller incorporating twist and heave as additional inputs, a thumb operated controller mounted on the sidestick, and a twist throttle grip similar to that on the AFTI/F-16. Additionally, some testing was done in the landing configuration using a thumbwheel mounted on a grip on the left hand side of the cockpit.

The 4-axis sidestick and the thumb operated miniature joystick provided an output proportional to the applied force. The force-deflection characteristics for these controllers were fixed. The pitch and roll axis of the sidestick had force-deflection gradients of approximately 40 pounds per inch with a maximum displacement of .4 inches at the grip center. The twist and heave axes were stiff enough that the pilots could not detect their presence when only conventional control responses were commanded. The twist force-deflection gradient was 12.0 inch-pounds of torque per degree of deflection with a 4 degree maximum deflection each side of neutral. The heave axis had a maximum deflection of ±1 inch about neutral with a force-deflection gradient of 320 pounds per inch.

The thumb operated miniature joystick, or thumb button controller, was mounted on top of the stick grip. The pilot would command an input by applying a force with his thumb on an inverted coolie-hat button. Maximum force was 5 pounds with a

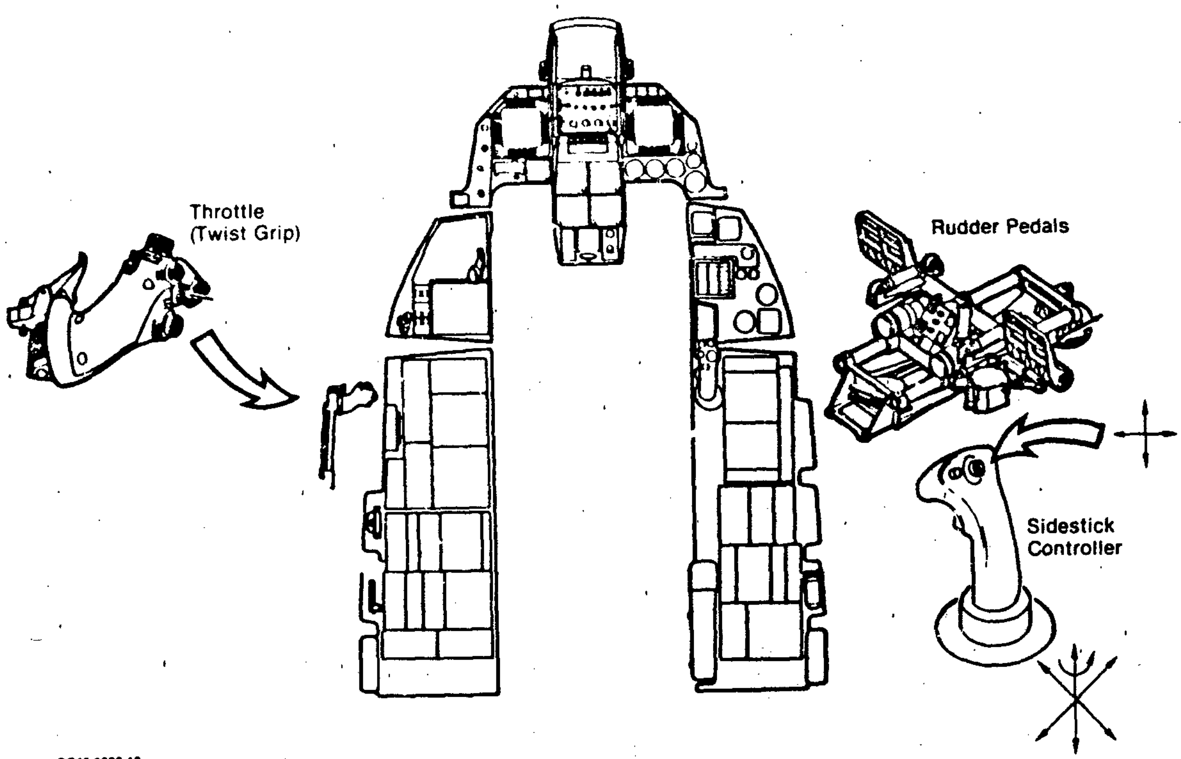

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Figure 31. Cockpit Controller Location

maximum deflection of approximately .06 inch, nearly isometric in appearance to the pilot. Figure 32 illustrates the control grip, including the twist axis and the thumb controller. Also shown are possible control modes which could be implemented on each of the control axes.

Past experience with sidestick controllers had indicated the desirability of an armrest, both for steadying the pilot's arm and providing pilot workload relief. For this simulation an adjustable armrest was provided. The sidestick and armrest installation on the right cockpit console are shown in Figure 33. Depending on exact pilot seating position, the installation placed the pilot's elbow at approximately a right angle. This places the elbow close to the body with his forearm on the armrest. This installation was dictated by cockpit constraints but is in close agreement with the recommendations of Reference 21.

The rudder pedals were a McFadden hydraulic loader system which offered great flexibility in configuration selection. Fore and aft neutral position was adjustable for pilot comfort. Rudder pedal position was used as the input to the simulation model. For this investigation the pedal deadband was set to zero, the friction to 1.5 pounds, and damping to 0.797 pounds per inch per second. These values were held constant throughout the simulation. The controller functions varied during the simulation were the breakout, linear gradient, and stop position. Each configuration was hand set and verified by the simulator operators prior to each run.

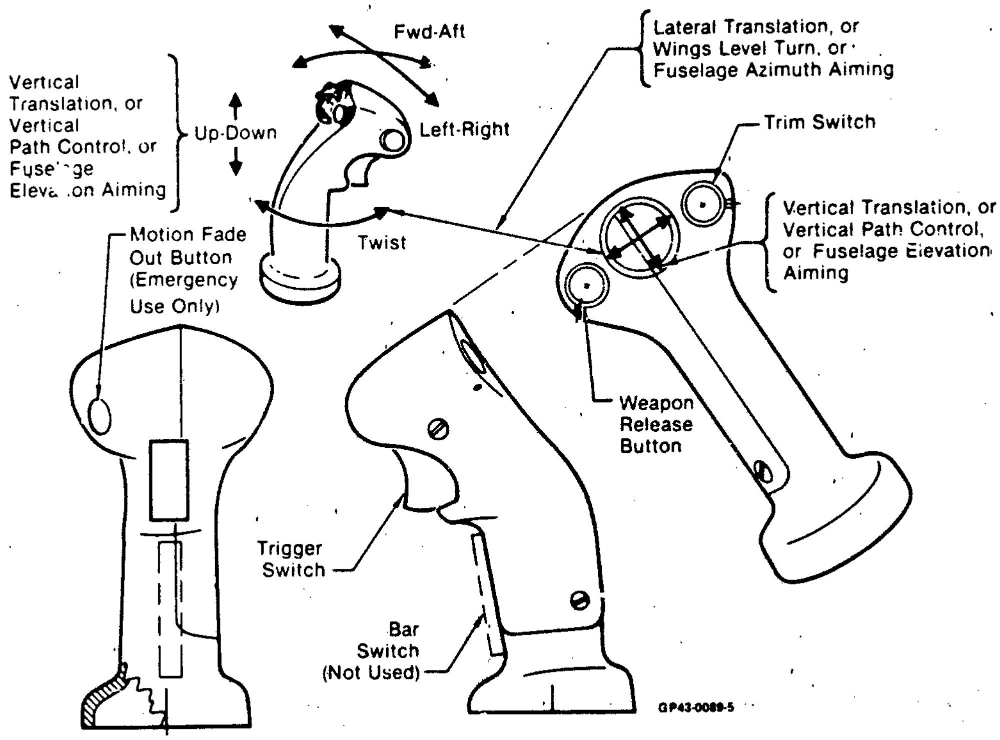

Figure 32. Sidestick Controller With Four Axis Motion

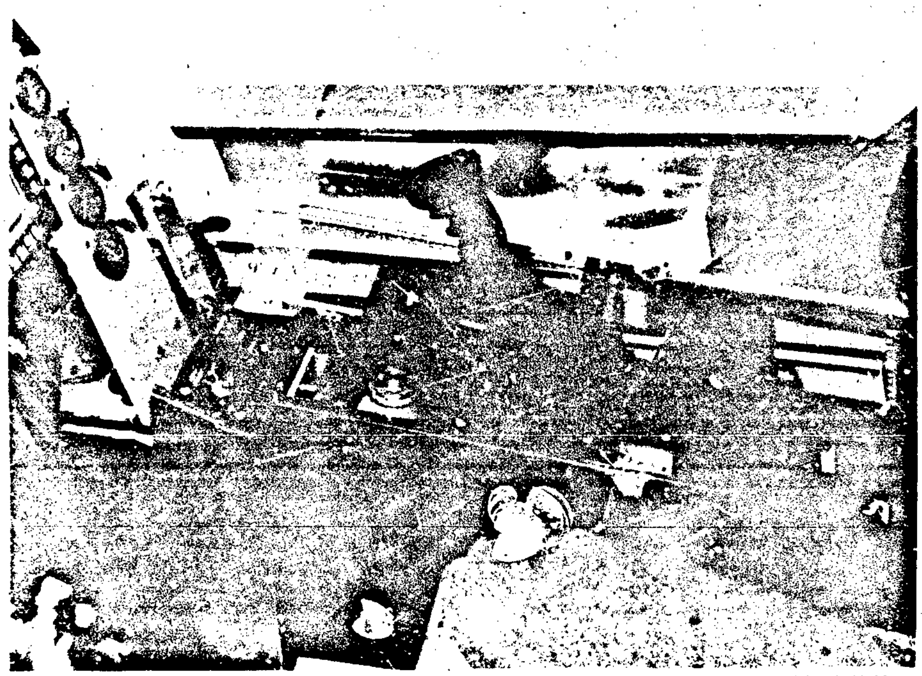

Figure 3_. Sidestick Controller and Armrest Installation

The throttle used during the simulation was similar to the one used on the AFTI/F-16. The throttle moves in a linear track parallel to the aircraft waterline. The grip extends horizontally from the track. The installation is shown in Figure 34. The unit contains an additional control feature which allows it to be twisted about the horizontal axis as shown in Figure 35. This implementation corresponds well to the responses generated by the uncoupled modes, particularly fuselage elevation aiming and vertical path control. Due to the concentration on lateral modes and some mechanization problems, only limited evaluations of its use during approach and landing were conducted.

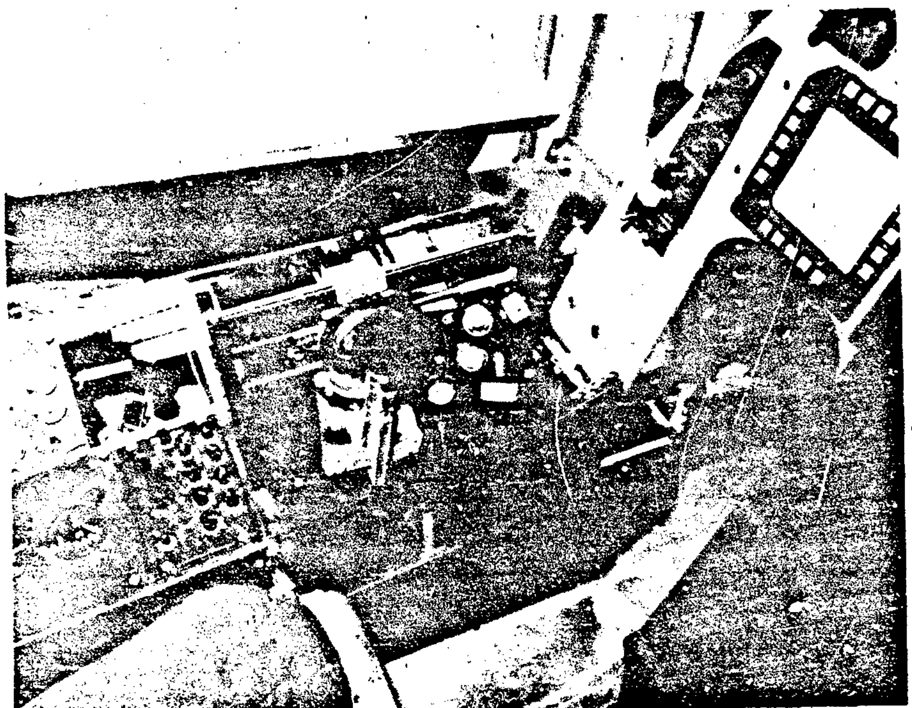
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Figure 34. Throttle Grip Installation

A thumbwheel controller mounted on a suitable grip and operated by the pilot's left hand was constructed. The installation of this controller is shown in Figure 36. Use of the controller required that the throttle throw be reduced to approximately one inch. This did not cause serious problems due to task and dynamics selection which minimized or eliminated any change in throttle position. Such an installation is obviously not suitable for actual aircraft use. This controller was used to gather pilot reaction to an unconventional controller which was not part of the primary controller (i.e., sidestick). The thumbwheel was spring loaded to center and could be rotated approximately 90° each side of neutral. Unfortunately, a tight schedule forced testing with the controller to begin soon after its fabrication by personnel at WPAFB and prior to a detailed calibration check.

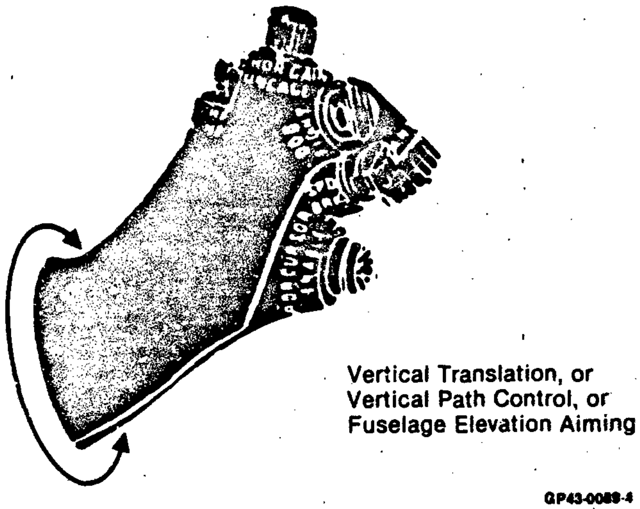

Figure 35. Twist Grip Throttle

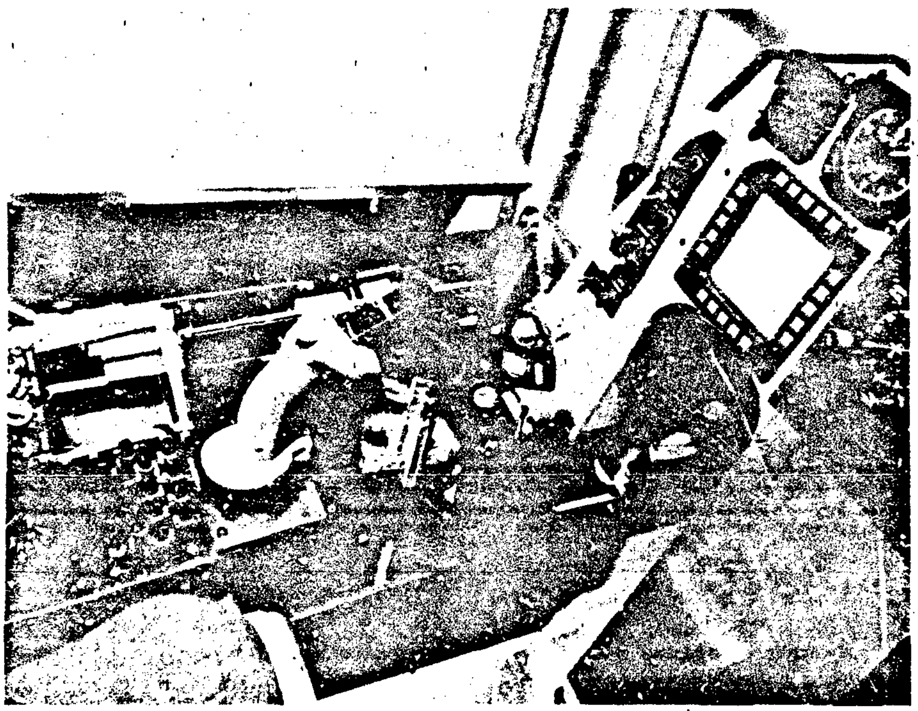

Figure 36. Thumbwheel Controller Installation

Due to the failure of the return spring during testing, it was not possible to conduct a post-test calibration to determine the exact force-deflection characteristics. Best estimates place the maximum input force at 5 pounds with a nearly linear force to rotation gradient. The thumbwheel was 1 inch in diameter. Comments on controller configurations will be based on estimated degrees of rotation to reach full command in the case of maneuver gradient and deadband examinations.

4. COCKPIT DISPLAYS - Pilot cockpit displays used in previous simulations and specific recommendations for display requirements to effectively implement uncoupled aircraft motion have been identified in previous sections. However, computational and time constraints forced the use of simplified display formats for this simulation. A standard set of fighter aircraft instruments was included on the cockpit panel. In addition, a Head Up Display (HUD) was projected on the simulation projection screen. The format of the HUD was a function of task and will be discussed in each task description. Pilot comments indicate that the simplified formats did not detract from the fidelity of the simulation.

5. AIRCRAFT MODEL DESCRIPTION - The generic aircraft program used for this simulation was developed by McDonnell Aircraft Company (MCAIR). The program is designed to allow simulation of handling qualities dynamics of an actual or hypothetical aircraft. This program has been used at MCAIR to evaluate aircraft handling qualities. The primary advantages of the program are 1) the ability for the user to quickly and easily implement configuration changes and 2) the speed of the computations.

The simulation uses transfer functions to specify body position relative to the velocity vector. The resultant accelerations produce changes in the velocity vector orientation. Gravity terms are included when calculating the accelerations. The major simplification used for this program was that the aircraft rolled around the velocity vector. This is in line with current control system design practices and allowed the pilots to "fly" the airplane without using the rudder pedals to coordinate rolls.

The characteristics necessary to specify the dynamics consist of frequencies, dampings, time constants, and steady state controller-response gains. For this simulation, the tasks were selected so as to minimize speed variations. By doing so, it was possible to hold the aircraft dynamics constant, thereby simplifying the model definition.

6. AIRCRAFT DYNAMICS - The aircraft conventional and uncoupled mode dynamics were selected to be representative of capabilities which could be incorporated in next generation fighter aircraft. Each set of conventional dynamics was fine tuned for each task so as not to detract from the controller evaluations. Once a set of aircraft dynamics had been selected, these dynamics were held constant during that series of evaluations. Details of the dynamics for each conventional and uncoupled mode are given in Volume II.

As mechanized, the uncoupled modes result in "pure" responses with no contamination to the other control axes. No drag due to uncoupled mode usage was added during this simulation. It was felt that this would unnecessarily complicate the evaluation of the controller characteristics. In actual use, the drag would produce a significant impact on aircraft performance. Any study aimed at a specific application of uncoupled motion must consider the impact of drag on mission effectiveness for the configuration being examined.

For some of the tasks it was desirable to use an atmospheric disturbance model which included turbulence and wind effects. These are described in detail in Volume II.

7. SIMULATION TASKS, DISPLAYS, AND PERFORMANCE MEASURES - Three basic tasks were used in the evaluation of the various controller-uncoupled mode configurations:

1. Air-to-Ground Weapon Delivery

2. STOL Fighter Approach and Landing

3. Air-to-Air Tracking

These tasks were selected because they represent the broadest range of application for uncoupled motion usage.

Where possible, every effort was made to keep the tasks as realistic and operationally oriented as possible. Each task had been outlined prior to the simulation. During pilot familiarization sessions, comments and suggestions on task improvements were solicited and incorporated where possible. Head up display formats were changed as necessary to facilitate effective mode usage. The following paragraphs briefly describe each of the tasks. Volume II contains a more complete discussion.

a. Air-To-Ground Weapon Delivery - Two air-to-ground tasks had been identified for use with the wings level turn mode: air-to-ground dive bombing and strafing. For the fuselage azimuth aiming mode, air-to-ground strafing was selected as the evaluation task. Both tasks were initiated from a pop-up maneuver.

For both tasks, a fixed, non-depressed aiming cross displayed on the HUD was used as an aimpoint. Additional information available to the pilot on the HUD included:

- Digital readouts of altitude, airspeed, and pitch attitude

- Aircraft velocity vector

- Horizon line

The HUD display is shown in Figure 37. The nondepressed, fixed sight is not indicative of operational display types on

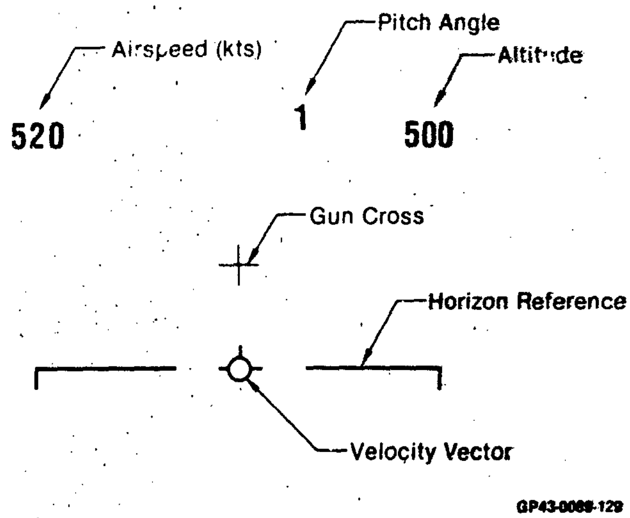

Figure 37. Air-to-Ground Head Up Display (HUD)

modern fighter aircraft. However, it did serve two purposes. The fixed sight removed sight dynamics as an experimental variable. The zero depression angle eliminates pipper pendulum effects during roll corrections. Elimination of pendulum effects had been sighted in previous efforts (References 44 and 52) as a major benefit of uncoupled aircraft motion. Modern control and sight dynamics can be used to eliminate pendulum effects without the added complexity of uncoupled control modes. The same display was used for the wings level turn and azimuth pointing modes.

A brief discussion of task details is given below for each uncoupled mode examined. Additional information on the following modes is given in Volume II.

(1) <u>Wings Level Turn</u> - The wings level turn evaluations began with the use of two tasks: dive bombing and strafing. Pilot comments indicated that while the tasks were of about equal difficulty, the dive bombing task really did not allow sufficient time to evaluate the controller characteristics. For this reason the dive bombing task was discarded.

The air-to-ground strafing task was initiated at 500 KCAS, 500 feet above ground level (AGL), six miles from the target. Three to four miles from the target the pilot initiated a 4g pullup to a 20° climb attitude. At 1500 feet AGL the pilot executed an unloaded 180° roll and pulled 2 to 4 g's. The pilot then rolled out in a 10° dive at 500 KCAS. Tracking consisted of stabilizing on one corner of the runway threshold, squeezing the trigger, translating to the opposite corner using wings level turn and again squeezing the trigger. If time permitted the pilot would also take a shot at the runway centerline. Recovery was initiated at approximately 1000 feet AGL. The distance between outside targets was approximately 275 feet. This profile is illustrated in Figure 38.

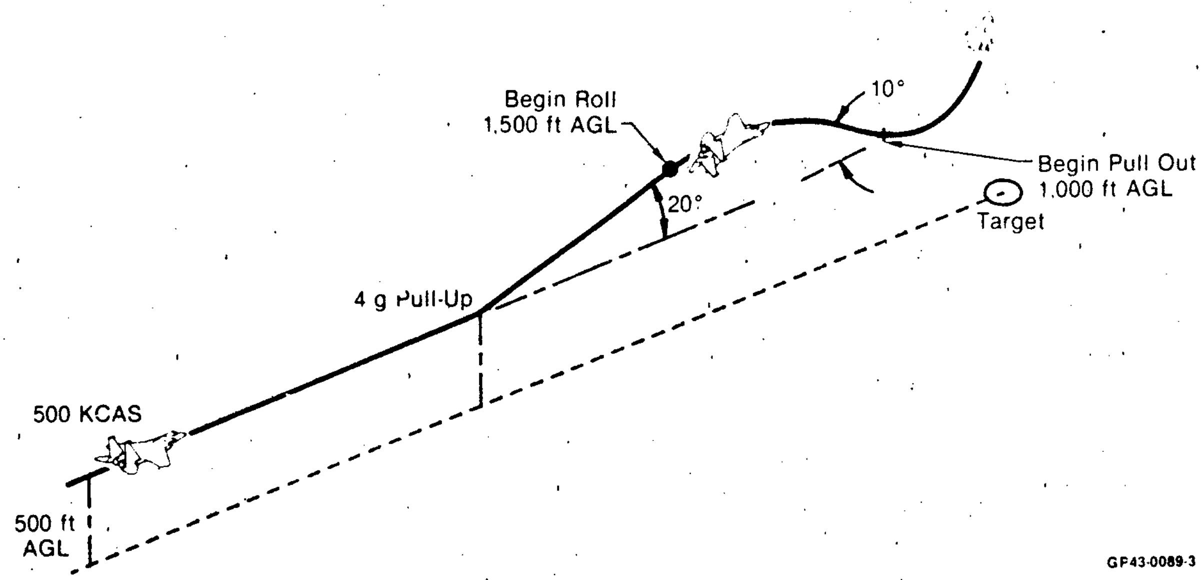

Figure 38. Air-to-Ground Strafing Pop-Up Maneuver

(2) Fuselage Azimuth Aiming - The fuselage azimuth aiming mode, also known as azimuth pointing, allowed the pilot to point the nose independent of the aircraft flight path. The primary task was an air-to-ground strafing profile using multiple targets. This task was initiated at the same conditions and used the same pop-up maneuver (Figure 38) as the wings level turn air-to-ground task outlined earlier. However, for this task three distinct targets were used. These targets consisted of three buildings approximately 50 feet wide by 30 feet tall spaced 500 feet apart perpendicular to the run-in line.

This task was felt to offer an excellent opportunity to evaluate controller characteristics. Rapid, accurate positioning was required. Additionally, operation about and through the neutral controller position allowed examination of breakout and deadband characteristics. The only major drawback was the relatively short duration and high activity required. Attempts by and comments from the pilots indicated that this task could not be accomplished using the aircraft conventional response capabilities.

b. STOL Fighter Approach and Landing - The landing task is another area where the use of uncoupled aircraft control may greatly increase precision and safety while reducing pilot workload. The increase in precision has significant implications for carrier based aircraft and aircraft operating from short fields due to runway denial or the use of unimproved airstrips.

The landings were conducted using the terrain board projection system. The HUD was superimposed on this display as done in the air-to-ground evaluations. HUD symbology included the information on the air-to-ground display plus an angle of attack indicator and instrument landing system (ILS) crosshairs. The HUD display is illustrated in Figure 39. The ILS crosshairs were driven with raw data expressing deviation from the desired approach path. Due to the use of raw data and the poor resolution of the crosshairs, all landings were made in visual meterological conditions. The angle of attack indicator provided a reference point for the trim angle of attack and was scaled to indicate ±1 degree deviations from this condition.

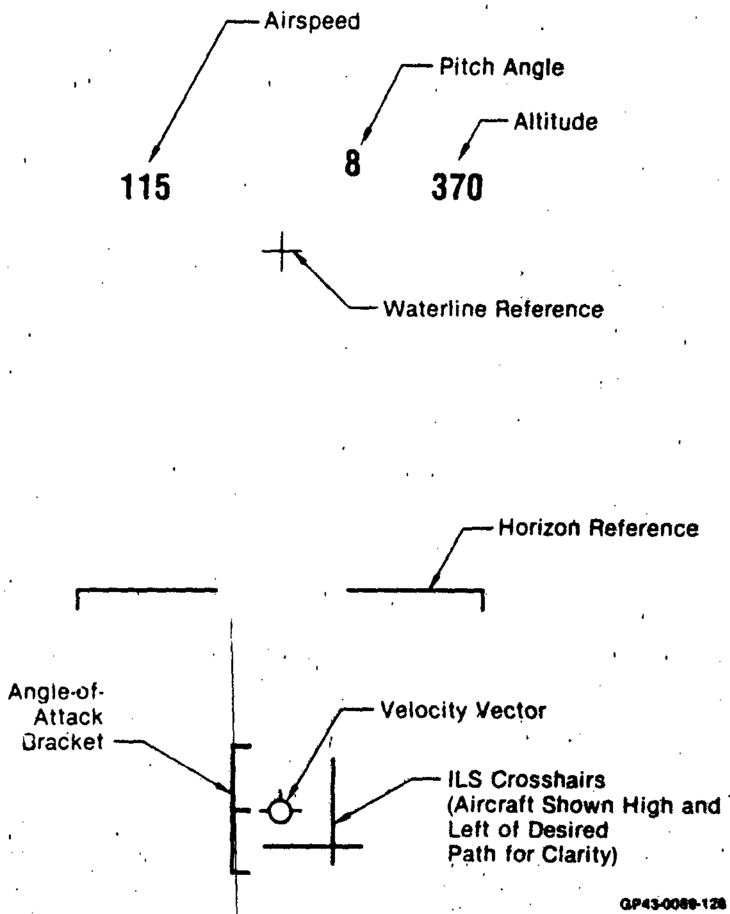

Figure 39. Approach and Landing Head Up Display

The task selected was to touchdown on a clearly defined 50 feet wide by 200 feet long segment of the runway in the presence of 3 feet per second rms vertical and horizontal turbulence and a 15 knot, 90° wind shear. The approach was initiated at one mile on a 4 degree glide slope. The approach speed was 115 knots. The task started with a 15 knot headwind until 330 feet AGL where upon the wind vector was linearly rotated with altitude to a 90° crosswind at 5 feet AGL.

In accomplishing this task, the wings level turn mode was used to establish and maintain the desired crab angle in the presence of the wind shear. This technique is much the same as that used with a conventional aircraft, however, wings level turn provided a direct control of the aircraft velocity vector lateral placement. Using this mode the pilots were allowed to touchdown in a crab. It should be mentioned that at the airspeed and crosswinds used, this technique resulted in approximately a 7 degree crab angle at touchdown. Pilot comments indicated this angle was near the maximum they would feel comfortable with in operational use.

The other modes evaluated in this task included lateral translation and fuselage azimuth aiming. The pilots were instructed to eliminate the majority of crab angle prior to touchdown when using these modes. The lateral translation mode allowed the pilot to cancel any crosswind effects while maintaining the aircraft heading parallel to the runway. When using the azimuth aiming mode, the pilot would establish the proper ground track using the conventional aircraft responses. The azimuth aiming mode was then used to eliminate the crab angle prior to touchdown. Pilot technique varied somewhat in that some pilots would wait to the last minute to use the mode while others would use the modes continuously during the approach.

A limited evaluation of controllers for the vertical translation mode was conducted during this phase. Two pilots participated in this evaluation. One pilot used the mode as a means of alleviating sink rate immediately prior to touchdown. The other pilot, during this phase, would use the conventional aircraft response to kill off some sink rate and then use the vertical translation as necessary to control touchdown point placement. In all other evaluations, the pilots made unflared landings.

The mode dynamics used during the above evaluations are described in detail in Volume II. The actual controller characteristics evaluated in the air-to-ground weapon delivery task are shown in Figures 40-45 while those evaluated in the approach and landing task are shown in Figures 46 through 52.

c. <u>Air-To-Air Tracking</u> - The literature survey had indicated several possible applications of uncoupled motion control in air-to-air combat. These included the use of wings level turn as a fine tuning method, the use of azimuth aiming for accurate weapons system aiming, and the use of translation as a defensive maneuver.

Initial plans were to examine the use of the wings level turn and azimuth pointing modes. During a task development session, potential tasks for use with the azimuth pointing mode were examined. It became apparent that there would be some difficulty in defining a continuous tracking task using this mode. Snap-sot type firing solutions were easily obtained, however, the pilot indicated that using the mode in continuous tracking of

Configuration No.	Breakout (lb)	Deadband (lb)	Maneuver Gradient (lb/g)	Maximum Force (Over Breakout) (lb)	Deflection at Maximum Force (in.)	Comments	No. of Evaluations	No. of Evaluation Pilots
1	7	[illegible]	15	15	0.5	Effect of Maneuver Gradient	1	1
2			25	25			1	1
3			[illegible]	[illegible]			1	1
4			45	45			1	1
5	4		[illegible]	25		Effect of Breakout	1	1
6	10						1	1
7	[illegible]						1	1
8	7		20	20	2	Effect of Maneuver Gradient	9	5
9			[illegible]	40			8	5
10			60	60			8	5
11			[illegible]	[illegible]			6	5
12	4		[illegible]	40		Effect of Breakout	4	3
13	10						3	3
14	[illegible]						2	2

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Figure 40. Controller Characteristics Evaluated for Air-to-Ground Weapon Delivery
Wings Level Turn Mode Rudder Pedals

Configuration No.	Breakout (in.-lb)	Deadband (in.-lb)	Maneuver Gradient (in.-lb/g)	Maximum Torque (Over Deadband) (in.-lb)	Deflection at Maximum Torque (deg)	Comments	No. of Evaluations	No. of Evaluation Pilots
15	0	[illegible]	6	6	0.5	Effect of Maneuver Gradient	4	4
16			12	12	1.0		5	4
17			18	18	1.5		7	4
18			24	24	2.0		7	4
19			36	36	3.0		5	4
20			48	48	4.0		4	3
21		[illegible]	24	24	2.0	Effect of Deadband	1	1
22		[illegible]					1	1
23		[illegible]					1	1
24		[illegible]					1	1
25		[illegible]	36	36	3	Effect of Deadband	1	1
26		[illegible]					1	1
27		[illegible]					1	1
28		[illegible]					1	1
29		[illegible]					1	1
30		[illegible]					1	1
31		[illegible]					1	1
32		[illegible]					1	1
33		[illegible]					1	1
34		[illegible]					1	1

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Figure 41. Controller Characteristics Evaluated for Air-to-Ground Weapon Delivery
Wings Level Turn Mode Twist Grip Sidestick

Configuration No.	Breakout (lb)	Deadband (lb)	Maneuver Gradient (lb/g)	Maximum Force (Over Deadband) (lb)	Deflection at Maximum Force (in.)	Comments	No. of Evaluations	No. of Evaluation Pilots
36	0	0.025	0.833	0.833		Effect of Maneuver Gradient	1	1
37			1.000	1.000			2	1
38			1.250	1.250			4	4
39			1.667	1.667			9	4
40			2.500	2.500			4	4
41			5.000	5.000			7	3
42		0.075	1.667	1.667		Effect of Deadband	2	1
43		0.125					5	2
44		0.250					4	2
45		0.375					1	1
46		0.500					3	2

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Figure 42. Controller Characteristics Evaluated for Air-to-Ground Weapon Delivery
Wings Level Turn Mode Thumb Button Controller

Configuration No.	Breakout (lb)	Deadband (lb)	Maneuver Gradient (lb/deg)	Maximum Force (Over Breakout) (lb)	Deflection at Maximum Force (in.)	Comments	No. of Evaluations	No. of Evaluation Pilots
1	7	0	0.5	5	0.5	Effect of Maneuver Gradient	1	1
2			1.0	10			1	1
3			1.5	15			2	2
4			2.5	25			3	2
5			3.5	35			1	1
6			4.5	45			2	2
7			5.4	54			1	1
8	4		2.5	25		Effect of Breakout	1	1
9	10						1	1
10	20						1	1
11	7		2.0	20	2	Effect of Maneuver Gradient	2	2
12			4.0	40			3	3
13			6.0	60			6	4
14			10.0	100			6	5
15			14.0	140			6	5
16			18.0	180			3	3
17	4		4.0	40		Effect of Breakout	1	1
18	10						1	1
19	20						1	1
20	4		6.0	60		Effect of Breakout	2	2
21	10						[illegible]	1
22	20						2	2
23	38.5						2	2
24	4		10.0	100		Effect of Breakout	2	1
25	10						1	1
26	7		2.0	20	3	Effect of Maneuver Gradient	3	2
27			4.0	40			5	3
28			6.0	60			4	2
29			8.0	80			2	2
30			12.0	120			1	1
31			14.0	140			1	1
33			16.0	160			1	1

GP43-0080-78

Figure 43. Controller Characteristics Evaluated for Air-to-Ground Weapon Delivery
Fuselage Azimuth Aiming Mode Rudder Pedals

Configuration No.	Breakout (in.-lb)	Deadband (in.-lb)	Maneuver Gradient (in.-lb/deg)	Maximum Torque (Over Deadband) (in.-lb)	Deflection at Maximum Torque (deg)	Comments	No. of Evaluations	No. of Evaluation Pilots
	0	0.48	1.2	12	1	Effect of Maneuver Gradient	3	3
			2.4	24	2		3	3
			3.6	36	3		4	3
			4.8	48	4		5	3
38		2.4	3.6	36	3	Effect of Deadband	2	2
39		4.8					2	2
40		9.6					2	2
41		12.0					2	2

GP43-0089-79

Figure 44. Controller Characteristics Evaluated for Air-to-Ground Weapon Delivery
Fuselage Azimuth Aiming Mode   Twist Grip Sidestick

Configuration No.	Breakout (lb)	Deadband (lb)	Maneuver Gradient (lb/deg)	Maximum Force (Over Deadband) (lb)	Deflection at Maximum Force (in.)	Comments	No. of Evaluations	No. of Evaluation Pilots
42	0	0.025	0.500	5.00		Effect of Maneuver Gradient	1	1
43			0.250	2.50			1	1
44			0.167	1.67			1	1
45		0.025	0.750	5		7.5 deg Authority	1	1
46			1.000			5 deg Authority	1	1

GP43-0089-80

Figure 45. Controller Characteristics Evaluated for Air-to-Ground Weapon Delivery
Fuselage Azimuth Aiming Mode   Thumb Button Controller

Configuration No.	Breakout (lb)	Deadband (lb)	Maneuver Gradient (lb/g)	Maximum Force (Over Breakout) (lb)	Deflection at Maximum Force (in.)	Comments	No. of Evaluations	No. of Evaluation Pilots
1	7	0	25	5	0.5	Effect of Maneuver Gradient	2	2
2			50	10			2	2
3			75	15			2	2
4			125	25			3	2
5			175	35			2	2
6			225	45			2	2
7			270	54			2	2
8	4		125	25		Effect of Breakout	1	1
9	10						2	2
10	20						1	1
11	38.5						1	1
12	7		100	20	2	Effect of Maneuver Gradient	4	3
13			200	40			2	2
14			300	60			3	3
15			500	100			2	2
16			700	140			1	1
17	4		200	40		Effect of Breakout	2	2
18	10						2	2
19	20						1	1
20	7		100	20	3	Effect of Maneuver Gradient	1	1
21			200	40			2	1
22			300	60			1	1
23			400	80			1	1
24			500	100			1	1

GP43-0069-84

Figure 46. Controller Characteristics Evaluated for Approach and Landing
Wings Level Turn Mode   Rudder Pedals

Configuration No.	Breakout (in.-lb)	Deadband (in.-lb)	Maneuver Gradient (in.-lb/g)	Maximum Torque (Over Deadband) (in.-lb)	Deflection at Maximum Torque (deg)	Comments	No. of Evaluations	No. of Evaluation Pilots
25	0	0.48	30	6	0.50	Effect of Maneuver Gradient	1	1
26			40	8	0.667		2	2
27			60	12	1.00		2	2
28			90	18	1.50		1	1
29			120	24	2.00		2	2
30			180	36	3.00		1	1
31			240	48	4.00		2	1
32		2.40	40	8	0.667	Effect of Deadband	2	1
33		9.60					1	1
34		14.40					1	1
35		4.80	60	12	1.00	Effect of Deadband	1	1
36		9.60					1	1
37		4.80	120	24	2.00	Effect of Deadband	1	[illegible]

GP43-0089-35

Figure 47. Controller Characteristics Evaluated for Approach and Landing
Wings Level Turn Mode Twist Grip Sidestick

Configuration No.	Breakout (lb)	Deadband (lb)	Maneuver Gradient (lb/g)	Maximum Force (Over Deadband) (lb)	Deflection at Maximum Force (in.)	Comments	No. of Evaluations	No. of Evaluation Pilots
38	0	0.05	2.50	0.500		Effect of Maneuver Gradient	1	1
39			3.13	0.626			1	1
40			4.17	0.834			1	1
41			5.00	1.00			1	1
42			8.33	1.67			1	1
43			12.50	2.50			1	1
44			25.00	5.00			2	1
45		0.025	5.00	1.00		Effect of Deadband	1	1
46		0.250					1	1
47		0.750					1	1

GP43-0089-86

Figure 48. Controller Characteristics Evaluated for Approach and Landing
Wings Level Turn Mode Thumb Button Controller

Configuration No.	Breakout (lb)	Deadband (lb)	Maneuver Gradient (lb/deg)	Maximum Force (Over Breakout) (lb)	Deflection at Maximum Force (in.)	Comments	No. of Evaluations	No. of Evaluation Pilots
1	7	0	2.24	15	0.5	Effect of Maneuver Gradient	1	1
2			5.22	35			1	1
3			1.49	10	2.0	Effect of Maneuver Gradient	1	1
4			2.99	20			3	3
5			5.97	40			3	2
6			8.96	60			2	2
7			14.9	100			2	2

GP43-0089-87

Figure 49. Controller Characteristics Evaluated for Approach and Landing
Fuselage Azimuth Aiming Mode Rudder Pedals

Configuration No.	Breakout (in.-lb)	Deadband (in.-lb)	Maneuver Gradient (in.-lb/deg)	Maximum Torque (Over Deadband) (in.-lb)	Deflection at Maximum Torque (deg)	Comments	No. of Evaluations	No. of Evaluation Pilots
8	0	0.72	1.19	8	0.67	Effects of Maneuver Gradient and Deadband	1	1
9			1.79	12	1.00		1	1
10			3.58	24	2.00		1	1
11		4.80	1.79	12	1.00		1	1
12		9.60	1.19	8.0	0.67		1	1
13			1.43	9.6	0.80		1	1

GP43-0089-88

Figure 50. Controller Characteristics Evaluated for Approach and Landing
Fuselage Azimuth Aiming Mode Twist Grip Sidestick

Configuration No.	Breakout (lb)	Deadband (lb)	Maneuver Gradient (lb/deg)	Maximum Force (Over Breakout) (lb)	Deflection at Maximum Force (in.)	Comments	No. of Evaluations	No. of Evaluation Pilots
1	7	0	0.75	5	0.5	Effect of Maneuver Gradient	1	1
2	↓	↓	2.24	15	↓		1	1
3			3.73	25			1	1
4			5.22	35			3	2
5			6.72	45			3	2
6			8.06	54			2	2
7			2.98	20	2.0	Effect of Maneuver Gradient	2	2
8			5.97	40	↓		2	2
9			8.95	60			2	2

GP43-0089-89

Figure 51. Controller Characteristics Evaluated for Approach and Landing
Lateral Translation Mode   Rudder Pedals

Configuration No.	Breakout (in.-lb)	Deadband (in.-lb)	Maneuver Gradient (in.-lb/deg)	Maximum Torque (Over Deadband) (in.-lb)	Deflection at Maximum Torque (deg)	Comments	No. of Evaluations	No. of Evaluation Pilots
10	0	0.48	1.78	11.9	0.99		1	1
11	↓	↓	2.67	17.9	1.49	Effects of Maneuver Gradient and Deadband	1	1
12			5.34	35.8	2.98		1	1
13		0.72	1.07	7.2	0.60		1	1
14		↓	1.34	9.0	0.75		1	1

GP43-0089-90

Figure 52. Controller Characteristics Evaluated for Approach and Landing
Lateral Translation Mode   Twist Grip Sidestick

a maneuvering target was like "trying to integrate six equations of motion in your head." These comments are in line with findings from the previous studies which indicated that the best implementation may be as an automatic mode controlled by the fire control system. As a result of these findings, only the wings level turn mode was examined.

The initial flight conditions were Mach .8 at an altitude of 1000 feet. Each evaluation was structured such that 60 seconds of tracking information was recorded. Because of the large area covered, no terrain board images were used. The pilot display consisted of a 277° sky-earth horizon representation, a projected HUD image as shown in Figure 53, and a computer generated target aircraft. The HUD symbology included digital pitch, airspeed and altitude information. The pilot was also provided with a horizon reference bar and velocity vector. The aiming cross was encircled by a 50 mil diameter reticle which included a range bar on the outside perimeter. The range bar was scaled such that the desired 1500 feet value occurred when the bar terminated at the six o'clock position. The pilots were encouraged to maintain a constant range to target. If the range fell below 1000 feet or beyond 2000 feet the run was aborted and the configuration re-evaluated at a later time.

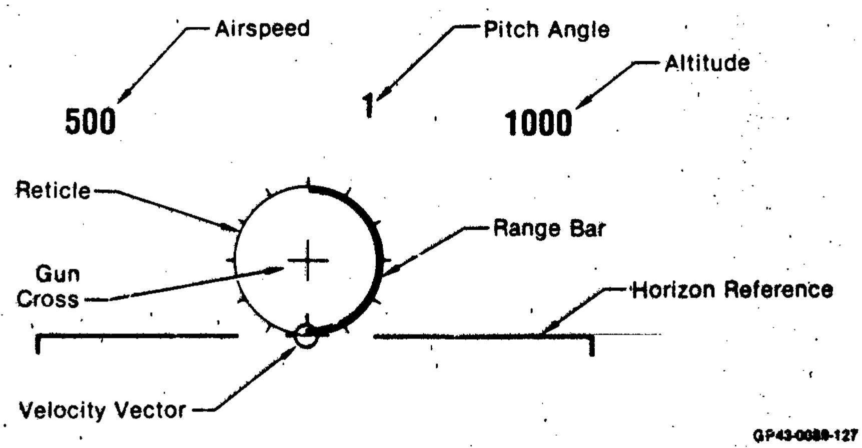

Figure 53. Air-to-Air Head Up Display
Target Not Shown for Clarity

Air-to-air fine tracking tasks were used exclusively. Two target types were recorded; one involving near constant altitude, moderate amplitude target roll motions and one involving small roll perturbations about a level 2g turn. Target airspeed was held at a constant magnitude. Details of the target dynamics and pilot tasks are given in Volume II. A summary of the controller characteristics evaluated in the air-to-air task is presented in Figures 54 through 56.

Configuration No.	Breakout (lb)	Deadband (lb)	Maneuver Gradient (lb/g)	Maximum Force (Over Breakout) (lb)	Deflection at Maximum Force (in.)	Comments	No. of Evaluations	No. of Evaluation Pilots
1	7	0	20	20	1	Effect of Maneuver Gradient	1	1
2			40	40			2	2
3			60	60			2	2
4	4		20	20		Effect of Breakout	1	1
5	10						1	1
6	15						1	1
7	15		60	60		Effect of Breakout	1	1
8	20						1	1
9	25						1	1
10	7		20	20	2	Effect of Maneuver Gradient	8	3
11			40	40			9	3
12			60	60			8	3
13	4		20	20		Effect of Breakout	1	1
14	10						1	1
15	15						1	1
16	25						1	1
17	1.5*		40	40		Effect of Breakout	1	1
18	4						6	3
19	10						4	3
20	15						6	3
21	20						3	2
22	25						2	2
23	7		20	20	3	Effect of Maneuver Gradient	1	1
24			40	40			2	1
25			60	60			3	2
26	4		60	60		Effect of Breakout	1	1
27	10						2	2
28	15						2	2
29	20						2	2

*Due to friction only

GP43-0089-81

Figure 54. Controller Characteristics Evaluated for Air-to-Air Tracking
Wings Level Turn Mode Rudder Pedals

Configuration No.	Breakout (in.-lb)	Deadband (in.-lb)	Maneuver Gradient (in.-lb/g)	Maximum Torque (Over Deadband) (in.-lb)	Deflection at Maximum Torque (deg)	Comments	No. of Evaluations	No. of Evaulation Pilots
30	0	0.48	12	12	1	Effect of Maneuver Gradient	9	3
31	↓	↓	24	24	2		16	3
32	↓	↓	36	36	3		7	3
33	↓	2.7	12	12	1	Effect of Deadband	1	1
34	↓	4.8	↓	↓	↓		1	1
35	↓	7.5	↓	↓	↓		1	1
36	↓	2.7	24	24	2	Effect of Deadband	6	3
37	↓	4.8	↓	↓	↓		6	3
38	↓	7.2	↓	↓	↓		1	1
39	↓	7.5	↓	↓	↓		3	2
40	↓	9.6	↓	↓	↓		2	1

GP43-0038-82

Figure 55. Controller Characteristics Evaluated for Air-to-Air Tracking
Wings Level Turn Mode Twist Grip Sidestick

Configuration No.	Breakout (lb)	Deadband (lb)	Maneuver Gradient (lb/g)	Maximum Force (Over Deadband) (lb)	Deflection at Maximum Force (in.)	Comments	No. of Evaluations	No. of Evaluation Pilots
41	0	0.05	1.25	1.25		Effect of Maneuver Gradient	5	3
42	↓	↓	2.50	2.50			5	3
43	↓	↓	3.33	3.33			7	3
44	↓	↓	5.00	5.00			7	3
45	↓	0.5	3.33	3.33		Effect of Deadband	5	3
46	↓	1.0	↓	↓			5	3
47	↓	1.5	↓	↓			4	1
48	↓	0.5	5.00	5.00		Effect of Deadband	1	1
49	↓	1.0	↓	↓			1	1
50	↓	1.5	↓	↓			1	1

GP43-0069-83

Figure 56. Controller Characteristics Evaluated for Air-to-Air Tracking
Wings Level Turn Mode Thumb Button Controller

9. PILOT SUBJECTIVE AND PERFORMANCE RESULTS - An extensive analysis of the pilot ratings, comments, and time history data was conducted. The analysis is covered in detail in Volume II. The analysis techniques used included Cooper-Harper ratings, histograms and time histories of control inputs and aircraft response, and pipper error data for the air-to-air task.

The results are used to augment data gathered during the literature survey to formulate the criteria presented in the following section.

SECTION V
PROPOSED CRITERIA AND DESIGN GUIDANCE

The ultimate goal of this study was to develop controller design criteria for incorporation in The Flying Qualities MIL-Standard (Ref. 68, Vol. 1). The MIL-Standard is a skeleton document in which requirements are given in verbal form with provision for insertion of numerical criteria by the procuring authority. The Flying Qualities MIL-Handbook (Ref. 68, Vol. 2) supplies recommended values for the criteria and supporting information.

The authors of Reference 68 drew heavily on the current Flying Qualities Military Specification MIL-F-8785C (Ref. 67) and its predecessor MIL-F-8785B. These documents are based on many years of flying qualities experience derived from flight test experience and dedicated flying qualities experiments. Independent control of six-degree-of-freedom uncoupled aircraft motion has no such extensive history of experience.

Consideration was given to writing the design criteria generated by this study in specific MIL-Handbook format. However, the proposed handbook organization, by axis of control, does not lend itself to presentation of controller requirements. A large number of requirements with many applicable paragraph numbers would be required. Since the criteria are preliminary at this stage, a more compact format was highly desirable. In the sections which follow, a group of qualitative and quantitative requirements will be listed. Each will be followed by a discussion section giving the reason for the requirement and guidance for application where appropriate.

1. <u>QUALITATIVE REQUIREMENTS</u> - In this section we will examine those requirements which apply to application of uncoupled aircraft motion. The intention is to provide general design guidelines applicable to incorporation of any cockpit controller for use with any uncoupled aircraft responses. For many of the qualitative requirements given here, it may appear that numerical values should be specified. Those cases will be addressed in the section on quantitative requirements which will propose recommended values and guidance for application based on the available information. The quantitative requirements will be broken down by control mode, controller type, and task as necessary.

Also, recommendations are included for cockpit displays. They are included because of their importance to the successful implementation of uncoupled aircraft motion control.

a. <u>REQUIREMENT: DEFINITION OF UNCOUPLED MODES</u>

The following table defines those motion variables which shall be commanded and constrained for each particular uncoupled mode of motion. The required equivalent system and bandwidth of each response shall be (as defined elsewhere in the Handbook).

Longitudinal:	Command:	Constraint:
Vertical Translation	$w, \hat{w}$	θ
Vertical Path Control	n_z	α
Fuselage Elevation Aiming	$\alpha, \dot{\alpha}$	n_z
Lateral-Directional:		
Lateral Translation	$v, \hat{v}$	ψ, ϕ
Wings Level Turn	r, n_y	β, ϕ
Fuselage Azimuth Aiming	$\beta, \dot{\beta}$	n_y

DISCUSSION: As indicated in the table, more than one possible command variable exists for some of the modes. The differences can be categorized as incremental changes in attitude or velocity, or as an increment in the rate of attitude or velocity changes. Contamination in each mode can therefore be determined by measurement of the constrained variable(s).

While the choice of commanded variable may not be directly related to the controller design problem, several observations were made during the course of this study. The YF-16 CCV and AFTI/F-16 aircraft command accelerations in both the vertical and lateral translation modes (References 46 and 74). In Reference 46, problems with the lateral translation mode were identified as a somewhat slow response and that the YF-16 CCV continued to drift slightly after the pilot had removed his control input. As a result, a velocity command system structure was developed in Reference 76, which used opposite command to stop the aircraft after the pilot removed his input. This system was not flight tested, however. The discussion of piloted evaluations of the AFTI/F-16 given in Reference 74 indicate that some pilots felt a velocity command system might be preferable to the current acceleration command system.

The fuselage aiming modes are shown as having two possible command variables. The YF-16 CCV and the simulation conducted as part of this effort used proportional control of the fuselage aiming angles. During the YF-16 CCV flight test program, the pilots indicated it might be better to command a rate of change of aiming angle. Using this technique it would be possible to "beep" in small corrections without the necessity of holding a continuous input. Such a pointing rate command system was implemented on the AFTI/F-16. While the pilots found the modes useful, particularly with practice, Reference 74 indicates that the pilots found the maximum rate of 2 to 3 degrees per second too slow. More importantly, the reference states that some pilots felt a pointing angle command system might be preferable to the rate command system tested. While there seems to be some conflict in the findings of the YF-16 CCV and AFTI/F-16 results, the answer may lie in the controllers utilized. Pitch axis elevation aiming could only be commanded by inputs to an isometric thumb button controller on the sidestick grip on the YF-16 CCV. Azimuth aiming could be commanded by either rudder pedal or thumb button inputs. On the AFTI/F-16, the rudder pedals are used to command azimuth aiming and a twist grip feature incorporated in the throttle is used to command elevation aiming. In the simulation conducted for this effort (henceforth to be identified as the controller simulation), the rudder pedals, a sidestick mounted thumb button and a twist feature built into the sidestick were examined as controllers for the azimuth aiming mode. It was found that while large amplitude proportional commands could be adequately controlled using the pedals or twist grip, the thumb controller was unacceptable. Even with reduced authority levels, sensitivity problems made the thumb button difficult to use for sustained inputs. These findings led to the theory that comments from the YF-16 CCV program concerning the desirability of the rate command system may have been influenced more by the inadequacy of the thumb controller rather than a basic problem with the mode. This is particularly true of pitch pointing, where only the thumb controller could be used on the YF-16 CCV. Alternately, the presence of a more desirable input method (i.e., the twist throttle grip for elevation aiming) may have led the pilots to the conclusion that a proportional angle command would be preferred.

For the direct force modes, wings level turn and vertical path control, there seems to be little doubt about the desirability of proportional control of flight path rate of change. Major comments noted in the literature concerned findings from the YF-16 CCV flight test program. The pilots noted that changes in mode sensitivity with flight condition during a dive bombing run were undesirable. In the AFTI/F-16 flight control system, the control system gains were scheduled with impact pressure to alleviate this problem. The wings level turn mode modeled in the controller simulation was also a constant Ny per unit of pilot input regardless of flight condition variation.

b. <u>REQUIREMENT: SENSE OF CONTROLLER IMPLEMENTATION</u>

Control motion shall be consistent with aircraft motion.

DISCUSSION: This requirement is one of the design criteria mentioned in Reference 65. The intent is to ensure compatibility among the pilot, the controller and the aircraft response. Pilot acceptability of the controller is one of the benefits of following this guideline. Uncoupled motion control is not a conventional response that is encountered in normal pilot training. The more natural the controller appears to the pilot, the less training time will be required to develop pilot technique. The best means of demonstrating consistency of control actuation and aircraft response is through the use of ground-based and in-flight simulation.

c. REQUIREMENT: CROSSTALK BETWEEN CONTROLLERS

Control activation shall not induce cross-coupled inputs in other axes.

DISCUSSION: As more and more control functions are made available to the pilot, the potential exists for cross-coupling of combined control functions placed on a single control grip. Reference 68 discusses crosstalk problems encountered between the pitch and roll axes of the YF-16 isometric sidestick controller. As the reference indicates, later operational experience with the F-16 movable sidestick rotated 12 degrees clockwise demonstrate very little crosstalk between pitch and roll. The authors of Reference 70, based on in-flight simulation results, recommend that the breakout forces of buttons and switches mounted on a sidestick should be less than one-half the breakout force of the basic sidestick. These examples serve to indicate the potential problems associated with crosstalk between conventional control axes. While the examples deal with sidesticks, the problem has not been limited to these types of controllers, similar problems have been noted to occur with conventional centerstick controllers.

The authors of Reference 65 recognized the potential problems involved in incorporating additional flight control modes on the pitch/roll controller. In a section of that report, entitled "Control Stick Grip with Special Flight Mode Controls" they caution the designer to ensure "control activation does not induce cross-coupled inputs in pitch/roll axes." The authors go on to recommend that the designer "evaluate in ground-based and in-flight simulation the (controller) locations for ease of operation and test of cross-coupling."

In the controller simulation, three controllers were examined which were part of the conventional pitch/roll controller, in this case a sidestick controller. These additional controllers were a thumb button, a twist axis input applied by twisting the sidestick grip, and a heave axis input applied by vertical forces to the stick grip. Each of these controllers demonstrated cross-axis coupling effects. The thumb button controller was mounted on the top of the stick grip. As a result, when forces were applied by the thumb, there was a tendency to push the stick in the same direction. Since only left-right inputs were made to the button, the result was a roll input to the sidestick. This problem was most noticeable in an air-to-ground task where rapid, large amplitude inputs were required. Notice that for this control, coupling only occurs when the uncoupled mode controller is used. With the twist and heave axis controllers, coupling was observed when uncoupled motion was applied. However, coupling from pitch/roll inputs into the uncoupled mode controller was also observed. For the heave axis controller, this was most noticeable for pitch inputs, while for the twist axis, coupling was most apparent during roll inputs.

Specific examples of the observed coupling are illustrated in the quantitative criteria section for each controller examined. Also, the effect of controller characteristics on the magnitude of coupling will be examined and guidelines for minimization developed.

The point of these examples is to emphasize that anthropomorphic coupling due to controller geometry is a real and recognized problem. In many low gain tasks, the pilot may automatically adjust his control input to account for the undesired input. The situation in which this problem can be most easily encountered and can also be the most dangerous is in high gain tasks that require large, rapid aircraft responses.

Another point which deserves comment was observed in the controller simulation. The coupling of roll axis inputs into the lateral-directional uncoupled mode controllers was often unobserved by the pilots. For the controllers examined, the resulting coupling was often in a direction compatible with the roll input (i.e., right roll coupled into mode resulting in motion of aircraft nose or velocity vector to the right). In no case should coupling occur which results in an aircraft acceleration or rotation in a direction opposite to those of the primary controller in use. This is supported by the results of negative control system coupling given in References 26 and 44.

Coupling tendencies should be checked during ground-based and in-flight simulation. Control input time histories should be examined as well as pilot subjective comments. Simulation tasks should be structured so as to produce a reasonable number of high gain, large magnitude inputs to highlight potential problems.

d. REQUIREMENT: MINIMIZATION OF LIMB CONTROLLER COUPLING

Sufficient physical restraint for the pilot's body and limbs shall be provided such that inadvertent inputs due to aircraft accelerations shall be minimized.

DISCUSSION: The feedthrough of aircraft accelerations through the pilot to the controllers represents another potentially dangerous coupling problem. This problem is compounded by the addition of previously unencountered large lateral accelerations available from some uncoupled aircraft responses.

Centrifuge experiments were conducted to investigate the effects of lateral accelerations on pilot tracking performance (References 58 and 59). The results indicate that additional pilot body restraints will be required for lateral acceleration in excess of 1 g. Additionally, significant control cross-coupling and inadvertent inputs into the sidestick controller, rudder pedals and throttle were observed due to increasing lateral accelerations.

This problem was also addressed in the controller simulation. Disturbances were injected into the motion drives which were independent of pilot input. These distrubances were of small magnitude and high frequency. A low frequency turbulence model was used to mask the appearance of the high frequency disturbances. No negative pilot comments were noted addressing motion feedthrough into the twist grip and thumb button controllers. The rudder pedal controllers appeared to be affected to a much lesser extent.

In-flight simulation and flight test are the best places to examine motion coupling effects due to the presence of full scale accelerations. Fixed base simulation is of no benefit in examining this problem. Centrifuge and motion base simulation experiments would be the only ways of examining this problem in a ground based environment. Each method has its limitations. The dynamics of a centrifuge are typically too slow to allow the simulation of actual aircraft responses and the examination of prolonged high lateral accelerations is of questionable benefit. However, advances in centrifuge response may prove beneficial. Motion base simulation, due to travel and amplitude restrictions, does not adequately represent the problems encountered in flight to provide definite quantitative information on motion feedthrough. The techniques developed in the controller simulation can be applied to indicate those areas where the problem is most likely to occur.

e. REQUIREMENT: CONTROL HARMONY

The limiting values of force specified for uncoupled aircraft motion controllers shall be compatible with the limiting values specified for conventional controllers in section 3.8.3 of the proposed MIL Standard and Handbook.

DISCUSSION: The intent of this requirement is to emphasize the importance of "harmony" in the forces required during normal controller usage. Most maneuvering requires the use of several control axes in combination. As such, the required combined forces must be within the pilot's capability.

During the controller simulation, certain problems with controller harmony due to controller displacement were also noted. The pilots found configurations requiring large rudder pedal deflections to lack harmony with the relatively small displacements of the sidestick controller. The twist axis of the sidestick also exhibited some harmony problems. The twist axis was nearly isometric, providing little motion at relatively high levels of torque. Some pilots noted that this did not seem compatible with the small, but noticeable, deflection of the sidestick in the pitch and roll axes.

As a minimum, it is recommended that ground based simulation using tasks requiring simultaneous multi-axis control inputs be conducted to ensure harmony in the force and deflection characteristics of the cockpit controllers.

f. REQUIREMENT: RESPONSE TO ZERO COMMAND

Each mode shall be self-cancelling, that is, upon removal of the pilot's command, the increment of the motion variable commanded by the pilot's uncoupled controller input shall return to zero. Requirements on the time to settle to the zero or commanded value shall be specified (elsewhere in the handbook).

DISCUSSION: This requirement is intended to ensure that removal of an uncoupled motion input returns all surfaces to the commanded position. Uncoupled motion control typically means multi-surface control with surface position determined by a computer. As a result, hysteresis problems should be easily managed to produce clean responses, since there are no mechanical linkages between the controller and the surface actuator.

Compliance with this requirement will also ensure minimum impact on aircraft performance. For proportional control modes, the control surfaces will return to their nominal positions for zero input resulting in minimum drag. Control modes which employ rate commands to achieve a desired angle change (i.e., a pointing rate command mode) should be provided with a means of ensuring long term return to nominal (e.g. zero sideslip). The pilot has no way of knowing exactly when such a mode has been neutralized other than to monitor a dedicated display parameter.

g. REQUIREMENT: CONTROLLER MOTION

Uncoupled motion controllers shall be designed to make use of controller deflection as a means of assisting the pilot in predicting aircraft response.

DISCUSSION: The problems with isometric controllers for conventional aircraft control have been well documented. The potential for the same problems to occur in the use of uncoupled aircraft motion are quite high.

Modern flight control systems rely on the use of computers to position control surfaces in response to a measured command from the pilot. As a result, there is no feedback (i.e., control feel) to the pilot. The design and implementation of an active force feedback to the controller is prohibitively expensive and complex. This lack of force feedback can lead to problems in predicting aircraft response, particularly if the aircraft response is slow. In discussing the design of sidestick controllers for conventional control, the authors of Reference 65 offer the following guidelines:

> ". . . choose total sidestick mechanical displacement so as to make the greatest use of a pilot's ability to predict aircraft performance for those portions of the flight envelope where the flight control system/aircraft cannot provide rapid, precise response. In instances where most pilots are known to experience difficulties in predicting aircraft

response, increasing total controller displacement in the axis concerned may enhance pilot capability to predict response."

Trade-offs in terms of speed of input and predictability of response were observed in the controller simulation. Several maximum deflection limits were examined on the rudder pedals as an uncoupled mode controller. Variations were one-half, two, and three inch deflections using a wings level turn mode and an azimuth aiming mode in an air-to-ground task. In an air-to-air tracking task, variations of one, two, and three inches were examined using a wings level turn control mode. The pilots indicated a preference for the one and two inch pedal throws in their comments. These were felt to be near the optimum in terms of speed of input and predictability of response. The shorter throw pedals aided in the speed with which a given command could be reached, while the definite motion of the pedals assisted in predicting the response. With the wings level turn mode, the one inch throw was appreciated for the rapidity with which the desired heading rate of change could be commanded. Thus, the shorter pedal throw resulted in a perceived quickening of the response. For the azimuth aiming mode the two inch deflection resulted in improved predictability of the response.

Problems were also observed with the twist grip sidestick controller and the thumb button controller. Both appeared nearly isometric to the pilots and both suffered somewhat from predictability problems. Neither controller featured a hard stop which indicated when a full command had been applied. Pilot comments indicated that the twist grip in particular would have been more acceptable if increased motion and a hard stop had been incorporated.

In conclusion, while there is a tendency to use controllers with the reduced complexity involved in isometric designs, it is important to note that the potential loss in predictability of response can be seriously detrimental to the aircraft flying qualities. The designer must trade off the benefits of improved predictability with the benefits of reduced design complexity. It is recommended that perceivable motion be included in any design, as well as a hard stop to indicate control saturation.

h. <u>REQUIREMENT: COMBINED UNCOUPLED AND CONVENTIONAL RESPONSE FROM A CONVENTIONAL CONTROLLER</u>

For those flight control modes blended with a conventional response on a standard cockpit controller, the requirements given for that controller in the proposed MIL-Standard and MIL-F-8785C shall apply.

DISCUSSION: This requirement is intended to apply to control modes which incorporate simultaneous blending of conventional and uncoupled response from a standard cockpit controller. There is little data from which to draw specific examples of control characteristics for combined control. There is a significant historical background for most standard conventional controllers. The only possible exception is sidestick controllers; however, even here the background of significant experience is growing rapidly. Reference 70 contains a good discussion and guidelines for the design of sidestick controllers. Since the addition of an uncoupled mode to a conventional response is typically meant to augment the conventional response, there is little reason to doubt that the standard controller requirements would apply.

However, it should be remembered that uncoupled control means multi-surface control. As a result, control paths will probably be by wire or light rather than direct mechanical linkage. Additionally, a computer will probably determine the necessary surface deflection at each flight condition. This offers great flexibility in tailoring the response characteristics for each task and flight condition. Therefore, those requirements which may be more lenient with characteristics of mechanical linkages must be examined in light of the control paths to be used in modern flight control systems. An example of one such characteristic would be breakout forces. In the past, breakout forces have been used to ensure centering of the controller. As a result it was necessary for the breakout force to be larger than any friction forces in the control linkage. Where no linkage exists, the design should comply with the lower end of the recommended range of breakouts. The designer should also recognize that some breakout is beneficial in providing an indication of neutral controller position, thus the lower limits on acceptable breakout are given in the existing requirements.

The maneuver enhancement mode examined on the YF-16 CCV is one example of combined control. In Reference 46, at least one pilot indicated concern over the response of the aircraft when encountering heavy turbulence. The pilot found the resulting rapid movements of the flaperons to be disconcerting. Additionally, there appears to be some concern over the onset rate of normal load factor and pitch rate in some of the maneuver enhancement modes. High onset roll rates of conventional aircraft have been shown to cause degradation in pilot acceptance (Reference 57).

While some knowledge of acceptable controller characteristics can be gained from ground based simulation, ultimate acceptability must be demonstrated in in-flight simulation and flight test. As indicated in Reference 75, the actual accelerations encountered in-flight can have a significant impact on acceptability.

i. <u>REQUIREMENT: PILOT DISPLAYS</u>

A display shall be provided which unambiguously informs the pilot what aircraft modes are available, and which accurately shows the final impact on aircraft orientation and velocity vector as a function of control inputs.

Information supplied to the pilot shall include at least:

1. Velocity vector (flight path)
2. Uncoupled modes activated
3. Saturation of command indication for any mode
4. Lateral acceleration/velocity or sideslip angle.

These requirements are in addition to the standard information presented to the pilot.

DISCUSSION: It may seem strange to include display requirements when discussing uncoupled mode controller characteristics. However, significant portions of the literature review indicated the importance of proper displays on successful implementation of uncoupled aircraft responses.

The use of Head Up Displays (HUD) in modern fighter aircraft has provided a unique and exceptional method of presenting information to the pilot. While care must be taken to avoid saturating the pilot's abilities to process this information, some minimum requirements have been identified for uncoupled mode usage. Item 1, a flight path marker, serves to accurately inform the pilot of the impact of his control inputs. This is particularly necessary when considering some of the unusual attitudes and responses available when combined uncoupled and conventional inputs are considered.

Multi-mode flight control systems provide the capability of commanding several different responses from the same controller as a function of mode selected. In such cases, the pilot must be provided with information concerning what modes are activated. This will serve to reduce the possibility of the pilot sensing what he interprets as an uncommanded response to a control input if he forgets what mode is active. If the flight control system is structured such that only one response is available from the controller at <u>all</u> times, item 2 may be considered as satisfied without providing a separate display item to the pilot.

Items 3 and 4 are closely related. One of the biggest problems identified in discussions with pilots from the AFTI/F-16 program (Appendix C) and the pilots of the controller simulation concerned indications of control saturation. Uncoupled mode responses are unique and often not totally perceptable to the pilot. Combine this with the variations in mode authorities with flight condition observed in many implementations and the pilot is presented with a significant problem when attempting to efficiently apply his control actions. An indication of when full available authority has been commanded would go a long way towards allowing efficient control force applications. Controller characteristics such as control movement and the use of hard stops tell the pilot when full controller commands have been applied. When a hard stop is provided, the pilot knows that additional force will not provide more response. Without a stop, the pilot may apply excessive forces to the controller in certain high gain situations. These excessive forces result in increased pilot fatigue and workload. For lateral-directional uncoupled modes, display of the uncoupled response achieved can also serve to provide saturation feedback information to the pilot.

Demonstration of adequate consideration of these requirements may be conducted by extensive full mission ground-based simulation. However, the designer should recognize the potential feedback cues provided to the pilot from motion-base and in-flight testing for full demonstration of compliance.

This concludes the discussion of qualitative requirements addressed to any planned manual uncoupled mode integration. In the next section quantitative requirements for specific controllers will be examined. It is suggested that the reader review that section even if his particular controller is not covered, since many significant trends for certain characteristics are reviewed. Additionally, if further research is planned, it is suggested that the conclusions and recommendations section of Vol. II be reviewed for lessons learned concerning simulation and control implementation for uncoupled aircraft controllers.

2. QUANTITATIVE REQUIREMENTS - This section will examine those controllers for which enough data is available to give a numerical range of recommended values. The intention is to provide the designer with a range of controller characteristics which have proven acceptable in previous applications. In general, the characteristics which will be addressed include: deflection characteristics, breakouts and deadbands, and the preferred range of maneuver gradients. Due to the previously mentioned problems with the information contained in the literature, the bulk of substantiating data will come from the controller simulation. Where possible, data from previous experiments will be used to augment this data base.

The proposed MIL-Handbook is organized by axis of control. In following this format, requirements for controller characteristics will be written for each mode. In the discussion section which follows each requirement, specific controllers which have been used for the uncoupled mode will be examined. Ranges of acceptable characteristics for that controller will be identified. Additional numerical values and comments will be included which will aid in meeting the qualitative requirements identified previously.

a. REQUIREMENT: WINGS LEVEL TURN CONTROLLER

Use of the primary wings level turn controller shall not require use of another control manipulator to meet the heading bandwidth requirements (shown elsewhere in the handbook). In addition, the controller characteristics shall meet the following requirements:

- o Breakout/deadband: __________
- o Maneuver Gradient: __________
- o Force/Deflection Characteristics: __________

DISCUSSION: This requirement is an expansion on the existing requirement of paragraph 3.6.1.2.1c of the proposed MIL-Handbook. The specific controller characteristics listed are felt to be the primary characteristics for determining controller acceptability. The controllers which will be examined specifically in this discussion are rudder pedals, a twist input to a sidestick controller, thumb button controllers, and two types of thumb wheel installations. These represent controllers for which sufficient information is available to arrive at numerical guidelines for controller design.

RUDDER PEDALS - WINGS LEVEL TURN MODE DISCUSSION: Many studies have examined the use of rudder pedals for control of the wings level turn mode. The majority of these studies were aimed at proof of concept for the uncoupled mode and did not perform detailed variations of mechanical controller characteristics such as breakout/deadband or force/deflection characteristics. Several studies did examine variations in pedal sensitivity, that is the unit pilot input per unit aircraft response in the steady state. However, variations in system authority and mode purity often make it difficult to compare results in hopes of developing any reasonable criterion.

Two studies, References 40 and 41, performed the first detailed variation of controller parameters. Reference 40 describes the initial efforts to implement direct side-force control on the NT-33. Comments on the evaluation of the wings level turn mode indicate the pilots preferred an 80 lb/in force-deflection gradient over a 130 lb/in gradient. Unfortunately there is no description of the amount of controller input that was required to achieve full command, so no maneuver gradient can be calculated. In Reference 41, the direct side-force capability of the NT-33 was used to simulate the Northrop A-9A wings level turn mode. Again, no description of input magnitude required was given. However, variation in force/deflection gradients were performed with 48 lb/in giving improved performance over 16 and 36 lb/in cases. All of the Northrop configurations incorporated sideslip "lead" to improve the wings level turn heading control. Pilot comments indicated that a 60 lb/in gradient on a configuration without "lead" was felt to be too heavy. Another interesting variation was conducted involving combinations of breakout and hysteresis in the rudder pedals. The pilots found they had more precise lateral control with a breakout/hysteresis combination of 3.5/3.0 lb than with a 7/6 lb combination. It was felt that the lower combination resulted in a more harmonious control system and thus provided more accurate pipper control. The evaluation task for this study was air-to-ground dive bombing.

In Reference 42, the rudder pedals were also used as the wings level turn controller in a dive bombing task. The simulated aircraft was an F-8 with added direct side-force capability. The rudder pedal travel was 3 inches with a force deflection gradient of 8 pounds per inch. During the dive bombing run, approximately 1.0 g of wings level turn authority was available. Assuming that full command was reached at maximum rudder pedal travel, the maneuver gradient would be approximately 24 pounds per g. Breakout force of the pedals was 5.5 pounds. While no pilot rating data was given, a review of the pilot comments indicates no particular problems with the controller mechanization. The potential problem of motion coupling into the aircraft controllers was addressed. The pilots indicated that, based on observations during the motion-base simulation, control coupling would not be a major problem.

A fixed-base simulation of wings level turn dynamics commanded from the rudder pedals was conducted as part of the study in Reference 44. Variations in mode dynamics and maximum lateral acceleration authority were conducted. As part of this effort, variations in maneuver gradient were also examined. The reference develops specific design criteria for the implementation of wings level turn control on future aircraft. The simulation task was air-to-ground dive bombing. Based on analysis of time history data, the minimum recommended mode authority was .5 g with a design goal of 1.0g's preferable. Additional criteria give specific mode dynamics required for good handling qualities. The rudder pedal mechanical characteristics were fixed. The maximum deflection was 2.5 inches with a force-deflection gradient of 44 pounds per inch and a breakout force of 7 pounds. The limiting criterion for maneuver gradient Level 1 flying qualities was established at a maximum of 110 lb/g and a minimum of 20 lb/g. The recommended design goal was established at 38 lb/g.

The YF-16 CCV flight test results are presented in Reference 46. As stated in the report, this effort was aimed at proving the viability of uncoupled aircraft control, rather than optimizing the individual response characteristics. One implementation allowed the use of the rudder pedals to command wings level turn. This mode/controller combination was evaluated in both air-to-air and air-to-ground tasks. The flight test program was somewhat limited in the information that could be derived for a single mode/controller combination due to the large number of test points to be covered. The largest single objection noted in the air-to-ground evaluation had to do with the variation in response with changing airspeed. Some sensitivity problems were noted in a few air-to-ground tasks, particularly a panel strafing task with a low pullout altitude (i.e., shorter final range to target).

The problems observed in the YF-16 CCV flight test program are reviewed in Reference 76 and recommended changes are developed. While these proposed changes were never flight tested on the YF-16 CCV, the information and suggested revisions deserve a closer review. Figure 57 was adapted from the reference. The figure illustrates the changes in control sensitivity with airspeed during the air-to-ground evaluations and the effect of increasing angle of attack for air-to-air tasks. Also shown are typical maximum pilot inputs for each of the tasks.

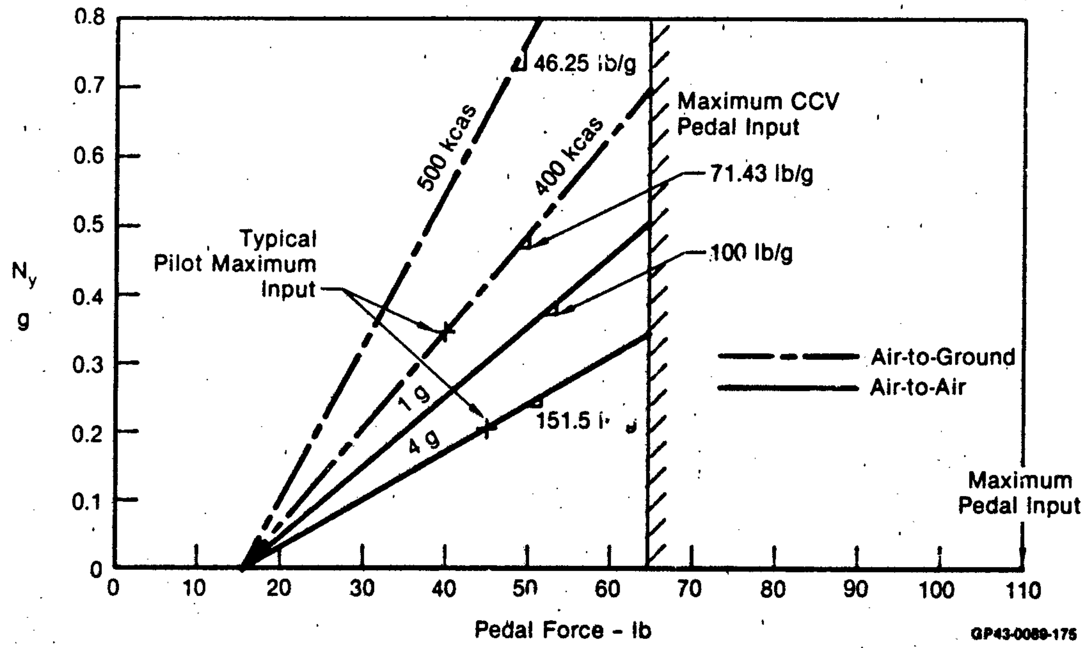

Figure 57. Ay Mode Control Sensitivity
Adapted From Reference 68

Another area which can produce sensitivity problems when operating through neutral is breakout force. The YF-16 CCV had a breakout plus deadband of fifteen pounds, ten pounds due to mechanical breakout and an electronic deadband of 5 pounds. One of the recommendations given in the reference was to delete the electronic threshold and employ only the mechanical breakout of the pedal assembly. This, combined with scheduling gains to reduce command sensitivity changes, and a new maneuver gradient which produced 0.3 g response for a 65 pound total pedal input were recommended to improve precision tracking. The report then goes on to develop a dual gradient based on a wings level turn authority of 2.0 g. This recommendation would lower mechanical breakout to 5 pounds, reach 0.3 g at 60 pounds of pilot input, then change the gradient to attain 2.0 g at a pilot input of 110 pounds. A triple gradient designed to smooth out the discontinuity at 60 pounds is also defined. The reader is cautioned to remember that there is no test data available to substantiate these gradient changes.

In the study of Reference 52, a 30°, high speed (720 kt) dive bombing task was used to evaluate wing level turn dynamics on a motion-base simulator. The target consisted of a primary bullseye with a secondary target laterally offset 1000 feet. The pilots rolled in on the primary target at 10,000 ft altitude. Approximately 50 percent of the time a light would indicate a switch to the secondary target. Release altitude was 5,000 ft. The mechanical characteristics of the rudder pedals were: 7 pound breakout, 3.25 inch deflection, 40 pounds per inch force-deflection gradient (45 lb/in was desired). Three levels of maximum authority were investigated using a nominal set of mode dynamics; these were 0.5 g, 0.75 g, and 3.0 g. Each was mechanized to occur at full pedal deflection which results in maneuver gradients of 260, 173, and 43.33 pounds per g, respectively. The 0.5 g case was found unacceptable to accomplish the primary task due to laggy response characteristics of the mode dynamics (equivalent to a 0.75 second time constant). The 0.75 g case was adequate for the primary task; however, transitioning to the secondary task was impossible in the available time before release. The 3.0 g authority was more than adequate. Based on analysis of the time history data, 50 percent of the time not more than 1 g of sideforce was used. The maximum observed lateral acceleration of 2.5 g was used momentarily. Though no definite statement is made, it is assumed that the 43.33 pound per g gradient was used for the rest of the simulation. Level 1 pilot ratings were collected for configurations having an equivalent time constant between 0.15 and 0.4 seconds. The equivalent time constant is defined as the time for the response to a unit step input to reach 63.2% of the steady state value.

The Princeton variable stability Navion was used in the experiments of Reference 26. While variation of mode response characteristics (including various mode "impurities") was the primary purpose, a variation of controller sensitivity was conducted. The following discussion is taken from the portion of the MIL-Handbook (Reference 68) dealing with results from this effort. Items inserted in square brackets are added to facilitate comparison with previous discussions. Figure numbers are from this report rather than Reference 68. Also DFC stands for Direct Force Control, wings level turn in this case.

> Some guidance regarding DFC control sensitivity may be found in the Reference 115 [26] flight tests of the wings level turn mode. The in-flight simulator was set up so that DFC control sensitivity could be varied. The pilots were asked to vary the control sensitivity of each new configuration to determine the optimum value, thereby eliminating it as a variable in the problem. It was found that the pilot ratings were not dependent on small variations in control sensitivity for either uncoupled or adversely coupled configurations.

The acceptability of configurations with large values of favorable yaw or roll coupling tended to be significantly more dependent on control sensitivity. This is shown by comparing Figure 59 for high favorable yaw coupling and Figure 60 for very high favorable roll coupling with Figure 58 for low coupling. It is interesting to note that the nominal value of control sensitivity used for the very low coupling case (0.008 g/lb) [125 lb/g] was found to be unacceptably high for the favorable coupling cases. The scatter in the data shown in Figure 60 is primarily due to pilot MP. In order to help explain why MP's ratings are higher than those of the other pilots, his comments have been annotated near the appropriate data points in Figure 60. It is clear that his poor ratings are based on his fundamental objection to utilizing roll coupling to improve tracking bandwidth, although his comments for the lowest sensitivity case indicate that adequate performance could be obtained in this mode. One interpretation is that pilot MP's rating of 5 was given to discourage intentional design of proverse roll coupling to improve tracking bandwidth. Hence, even though large values of favorable roll coupling may be inferred as acceptable to produce Level 1 flying qualities, the designer is cautioned against using such coupling to overcome an inherently low bandwidth. This is especially pertinent for configurations where the subject pilot was farther from the roll axis (than in the Navion) and therefore subject to more roll-induced lateral acceleration.

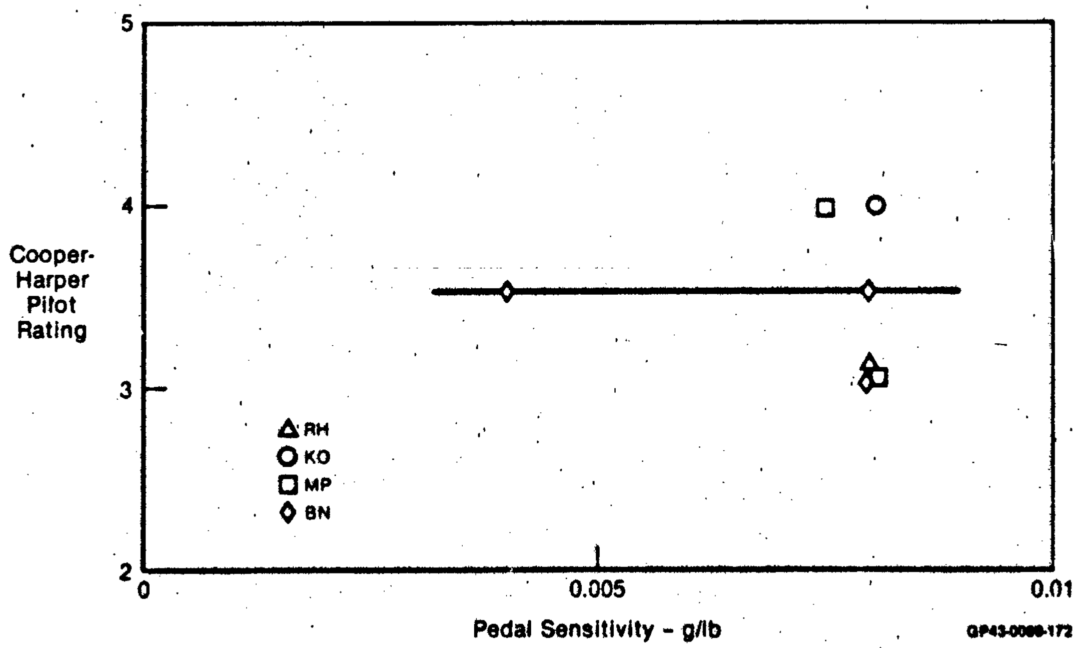

Figure 58. Effect of DFC Manipulator Sensitivity Configuration WLT1
Very Low Coupling From Reference 68

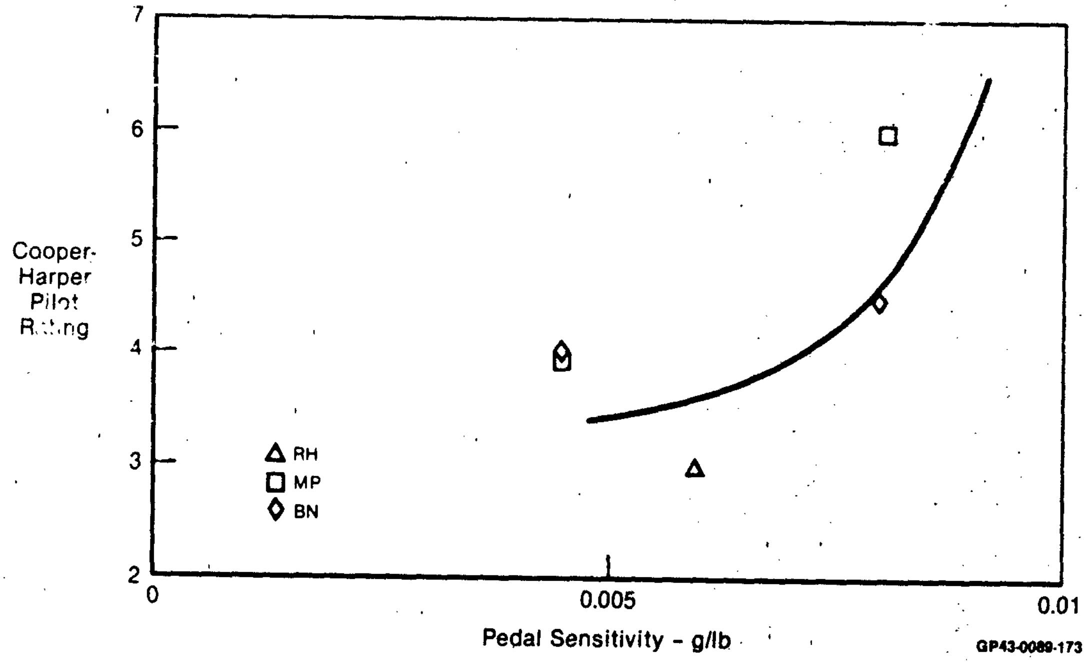

Figure 59. Effect of DFC Manipulator Sensitivity Configuration WLT5
High Favorable Coupling From Reference 68

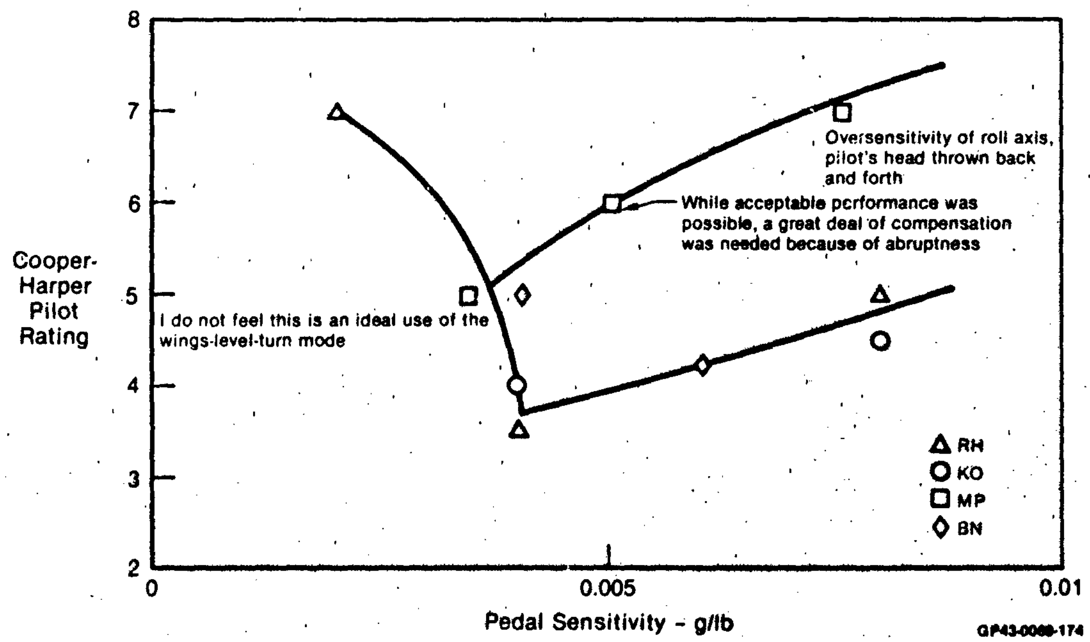

Figure 60. Effect of DFC Manipulator Sensitivity Configuration WLT12
Very High Favorable Roll Coupling From Reference 68

Examination of the air-to-ground data from Vol. II of this report indicates no clear trend for desired maneuver gradients or breakout forces. In addition, there is no apparent preference for one pedal displacement over another. The pilot rating results for the one-half inch deflection are shown in Figures 61 and 62. The two inch deflection results are presented in Figures 63 and 64. It is hypothesized that the rapid, dynamic nature of the task may account for some of the rating dispersion. However, similar types of results are indicated in Reference 44. The reader is cautioned that throughout the simulation the pilots tended to employ a non-linear use of the rating scale. This non-linearity manifests itself as a larger change in flying qualities when going from a Cooper-Harper (CH) rating of 3 to CH=4 (change in Level), than a change from CH=2 to CH=3 would represent (no change in Level).

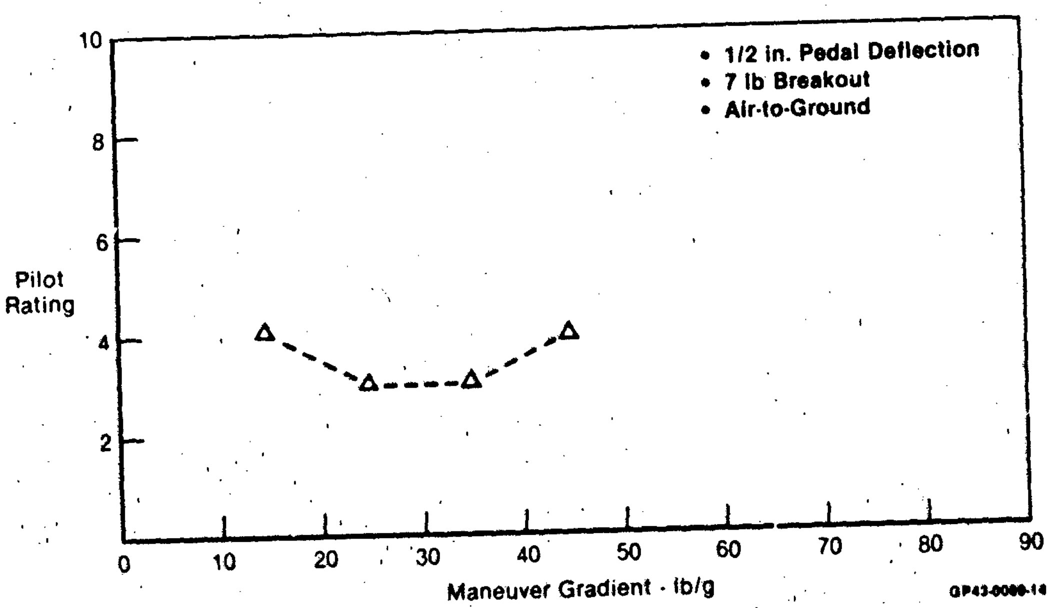

Figure 61. Pilot Rating vs Maneuver Gradient
Rudder Pedals Wings Level Turn Pilot 8

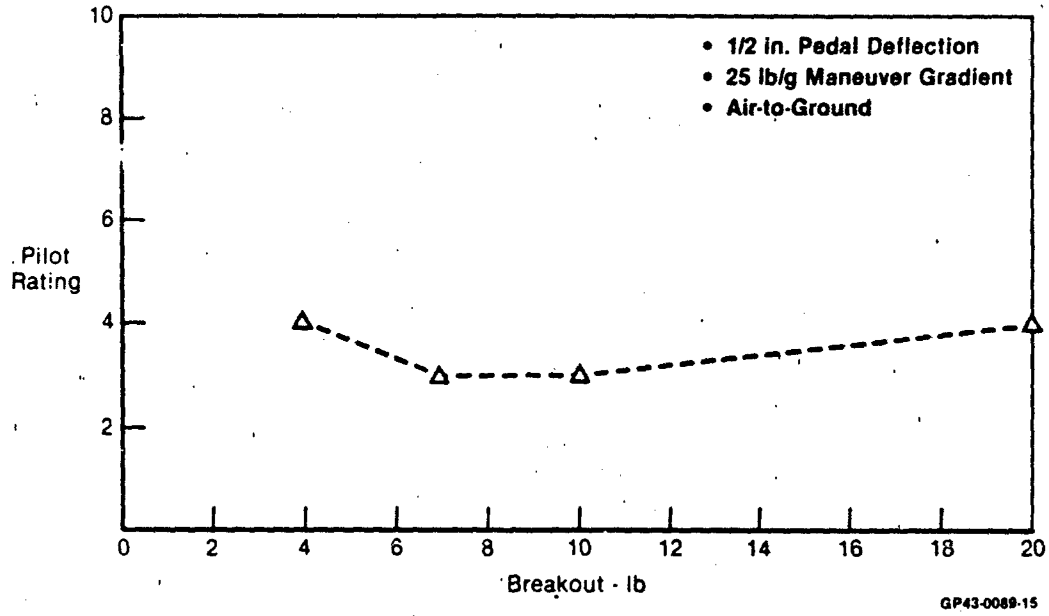

Figure 62. Pilot Rating vs Breakout
Rudder Pedals Wings Level Turn Pilot 8

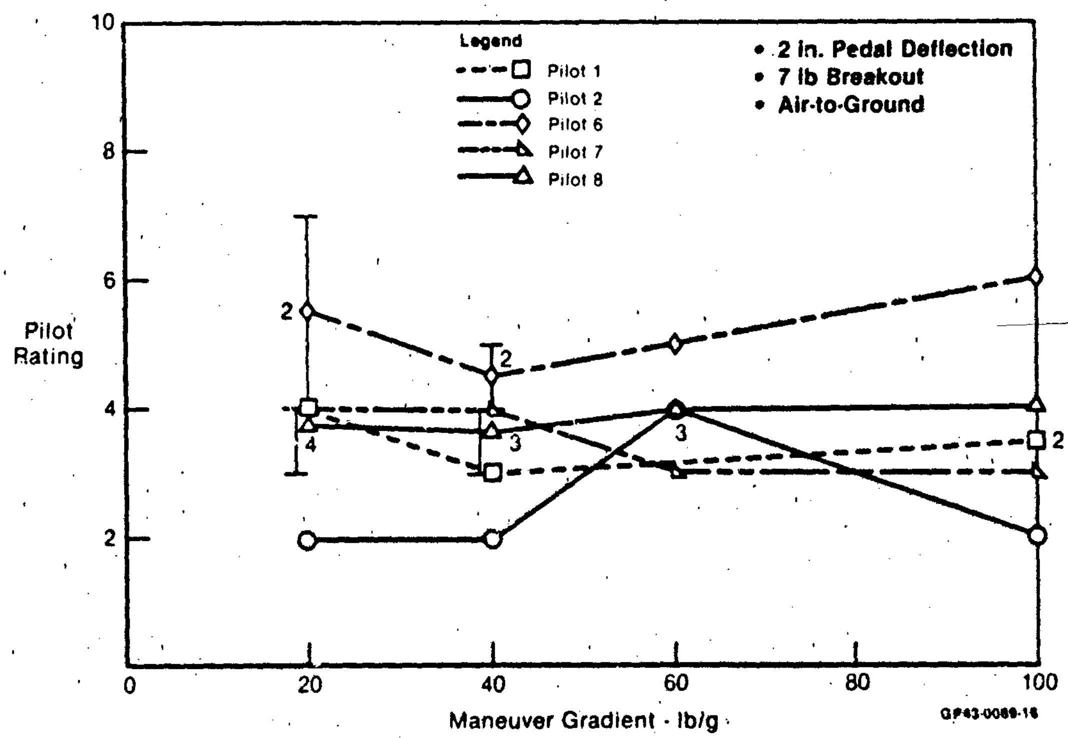

Figure 63. Pilot Rating vs Maneuver Gradient
Rudder Pedals Wings Level Turn

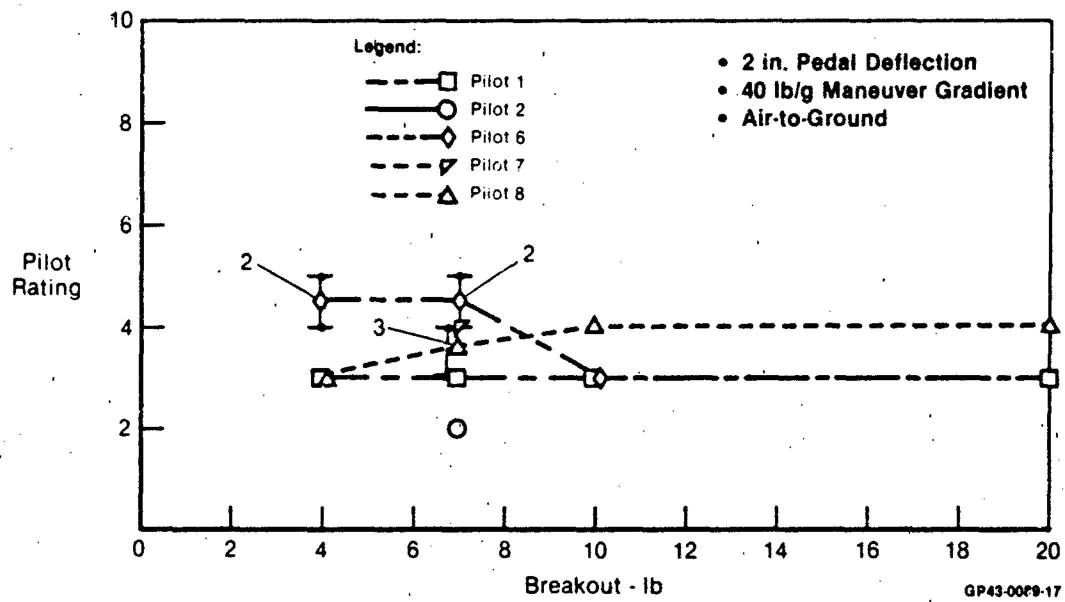

Figure 64. Pilot Rating vs Breakout
Rudder Pedals Wings Level Turn

The air-to-air tracking phase consisted of two tasks. The "level target" task consisted of the target performing moderate bank angle perturbations about a mean bank angle of zero degrees. The "turning target" task consisted of the target performing small bank angle perturbations about a mean bank angle of 60 degrees. In both tasks the target maintained near constant altitude and airspeed (520 knots at 1000 feet).

Three pilots, identified as 21, 22, and 23, participated in the air-to-air evaluations. All three had participated in the air-to-ground tasks.

Figures 65 and 66 compare Pilot 21's and 23's evaluation of the one inch maximum rudder pedal configurations. As indicated by his ratings, Pilot 21 liked the one inch throw. Pilot 23, on the other hand, indicated he had some problems making small inputs. With the 40 lb/g gradient he found himself overshooting the target during the turning target evaluations. Satisfactory results were obtained with the 60 lb/g gradient. The breakout variations for Pilot 21 had been done with a 20 lb/g maneuver gradient during the first simulation. Due to Pilot 23's preference for the 60 lb/g gradient, this value was used during this breakout variation. The difference in desired maneuver gradients is thought to be due to the differences in pilot technique mentioned during the simulation, i.e., Pilots 21 and 22 use of the toes versus Pilot 23's use of his whole leg due to his large size. The results of the variations are shown in Figure 66. It is interesting to note that Pilot 21, using the lighter gradient, appears to be more sensitive to breakout variations than Pilot 23 using the stiffer gradient. A review of the pilot comments in Appendix E indicates that Pilot 23 noticed the higher breakouts at the 15 lb level. He commented that the configuration seemed sluggish, especially around neutral; however, he felt the compensation required was minimal and assigned a CH=3.

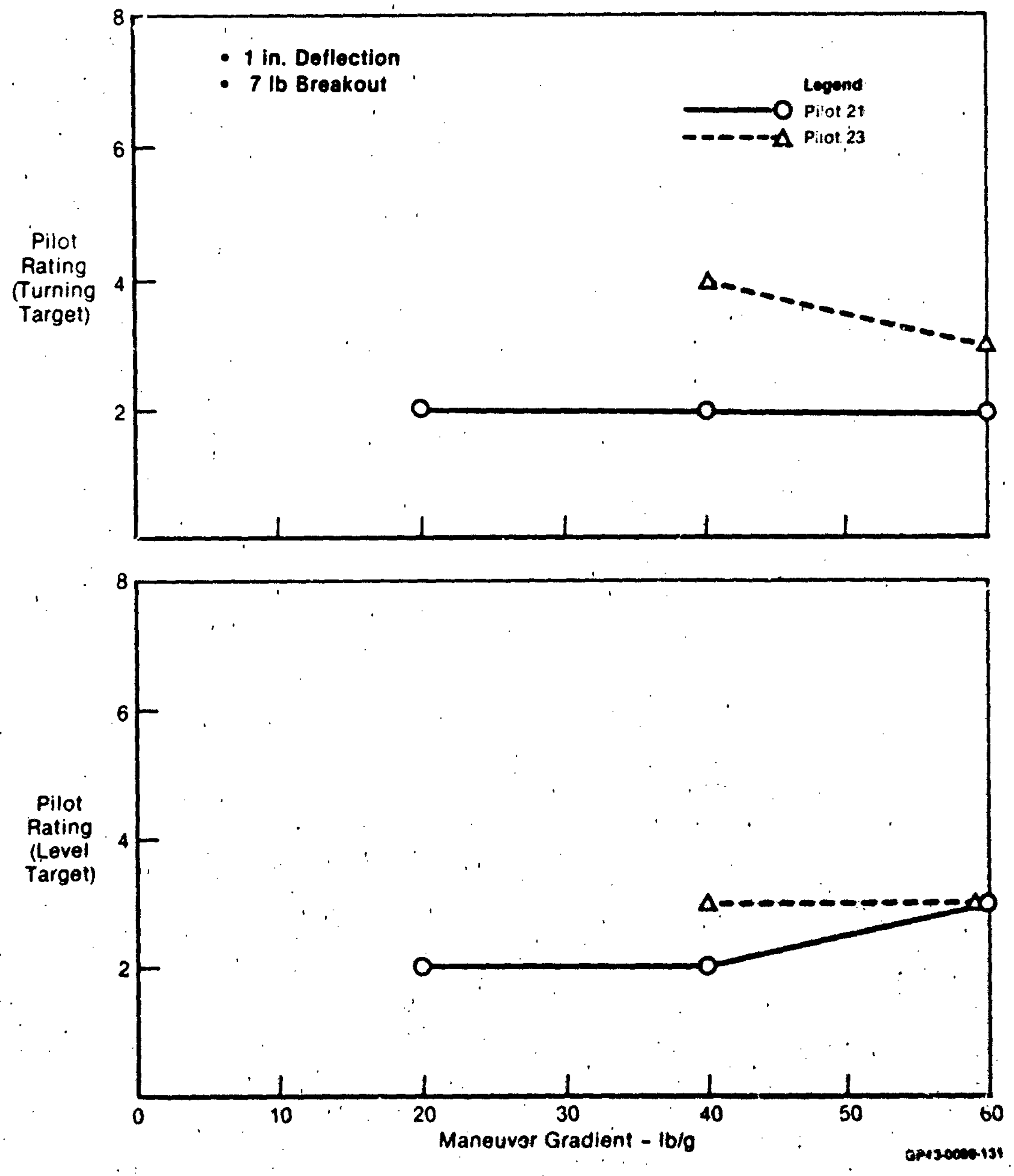

Figure 65. Pilot Rating vs Maneuver Gradient
Rudder Pedals . Wings Level Turn

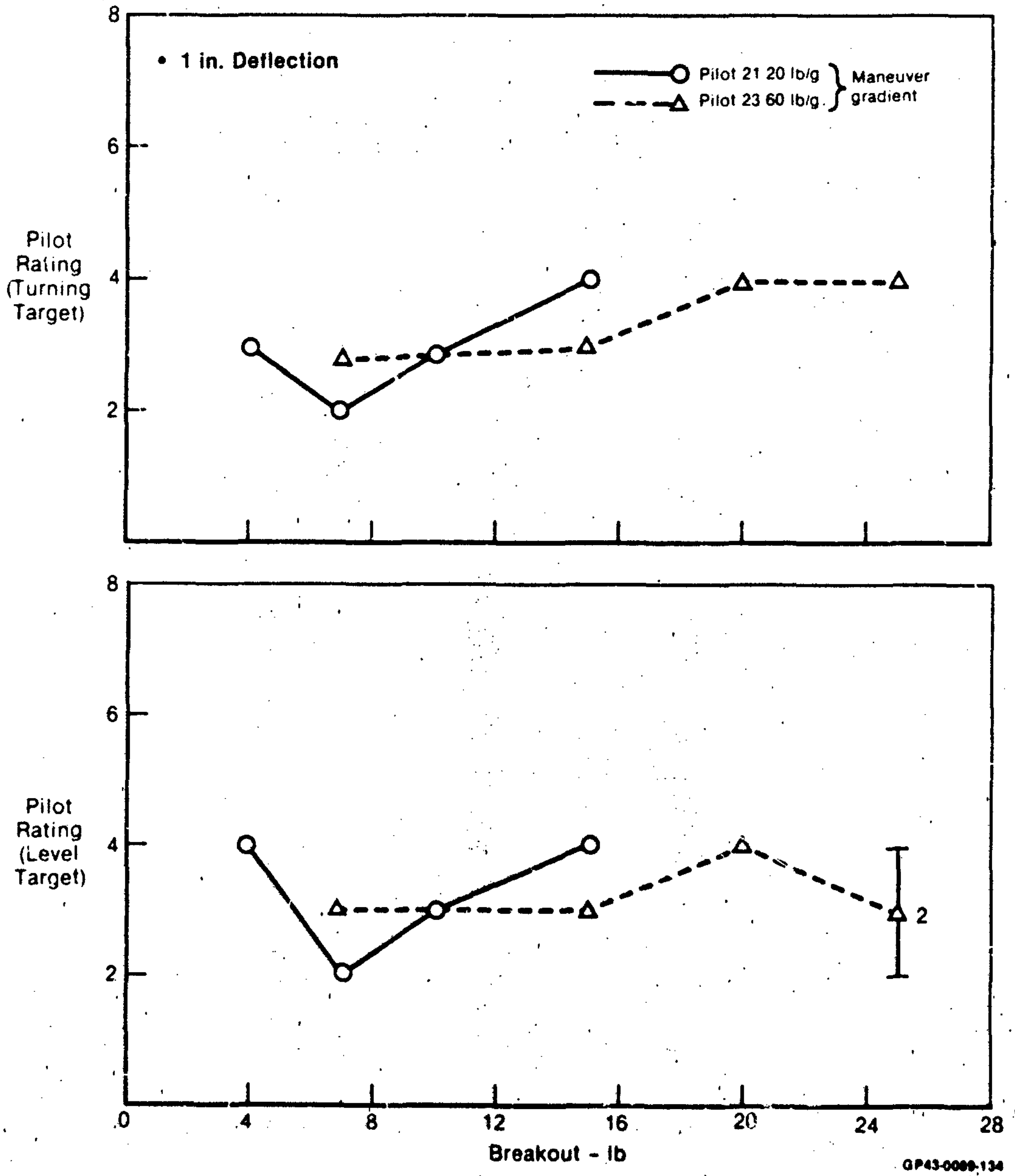

Figure 66. Pilot Rating vs Breakout
Rudder Pedals · Wings Level Turn

Figures 67 and 68 present the pilot rating data for the three inch pedal deflection configuration. Due to some experimentation with tasks, the level target data is not directly comparable. For these evaluations, the level target that Pilot 21 saw was executing 30% higher amplitude bank angles than the target used for Pilot 23. These are referred to as the faster target points on the plots. The turning targets were identical. Neither pilot really liked the three inch pedal deflection as compared to the shorter throws. Pilot 23 commented on some difficulties with predictability using the three inch throw. Pilot

21's comments for the 20 lb/g configuration emphasize the importance of proper maneuver gradient selection. His comments indicate that he perceived this configuration to have less damping, with considerable overshoots. Since the wings level turn response was modeled as a first order transfer function and the dynamics were never changed, this decrease in apparent damping can only be due to his rudder pedal inputs acting through the rudder pedal characteristics.

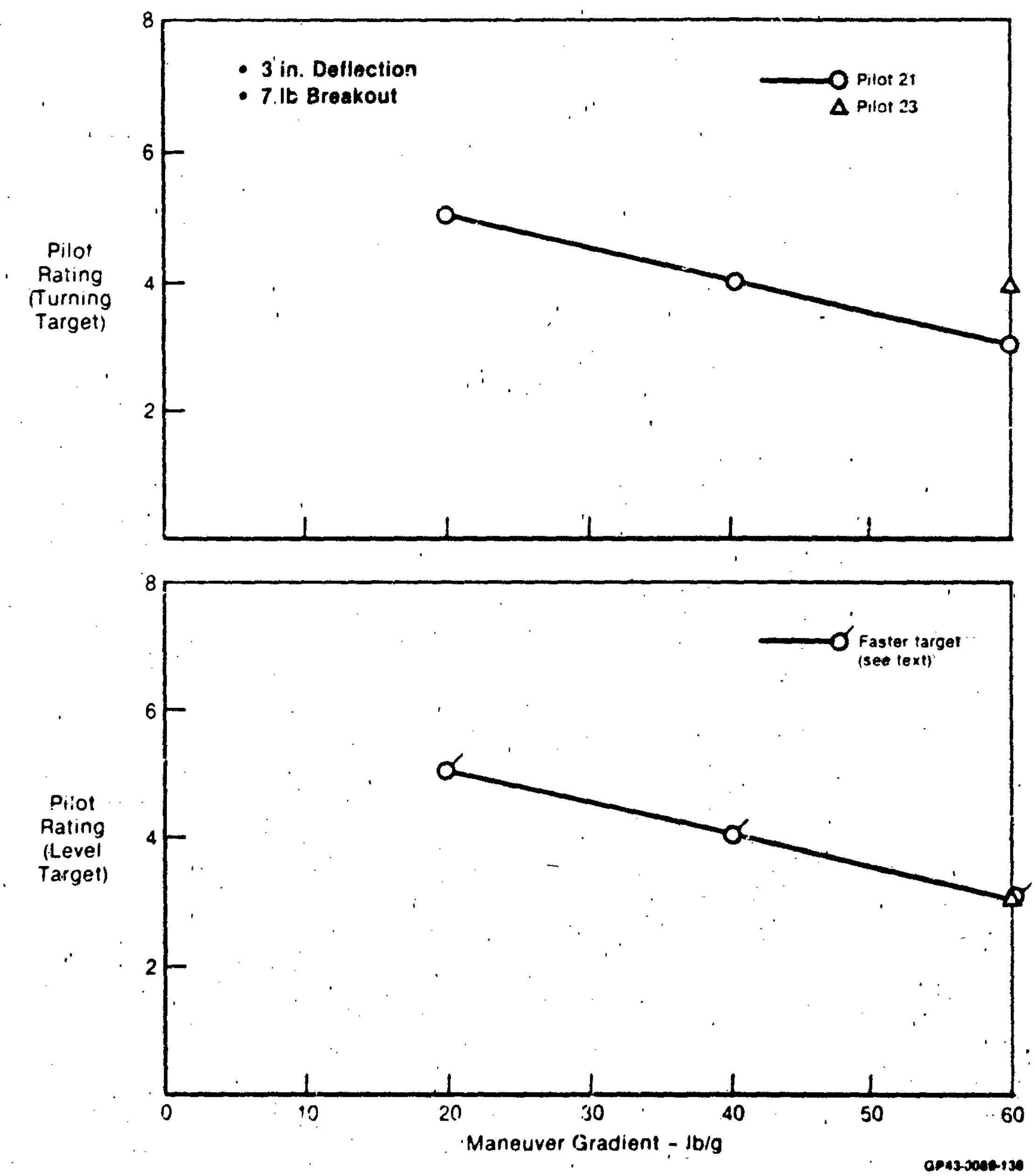

Figure 67. Pilot Rating vs Maneuver Gradient
Rudder Pedals Wings Level Turn

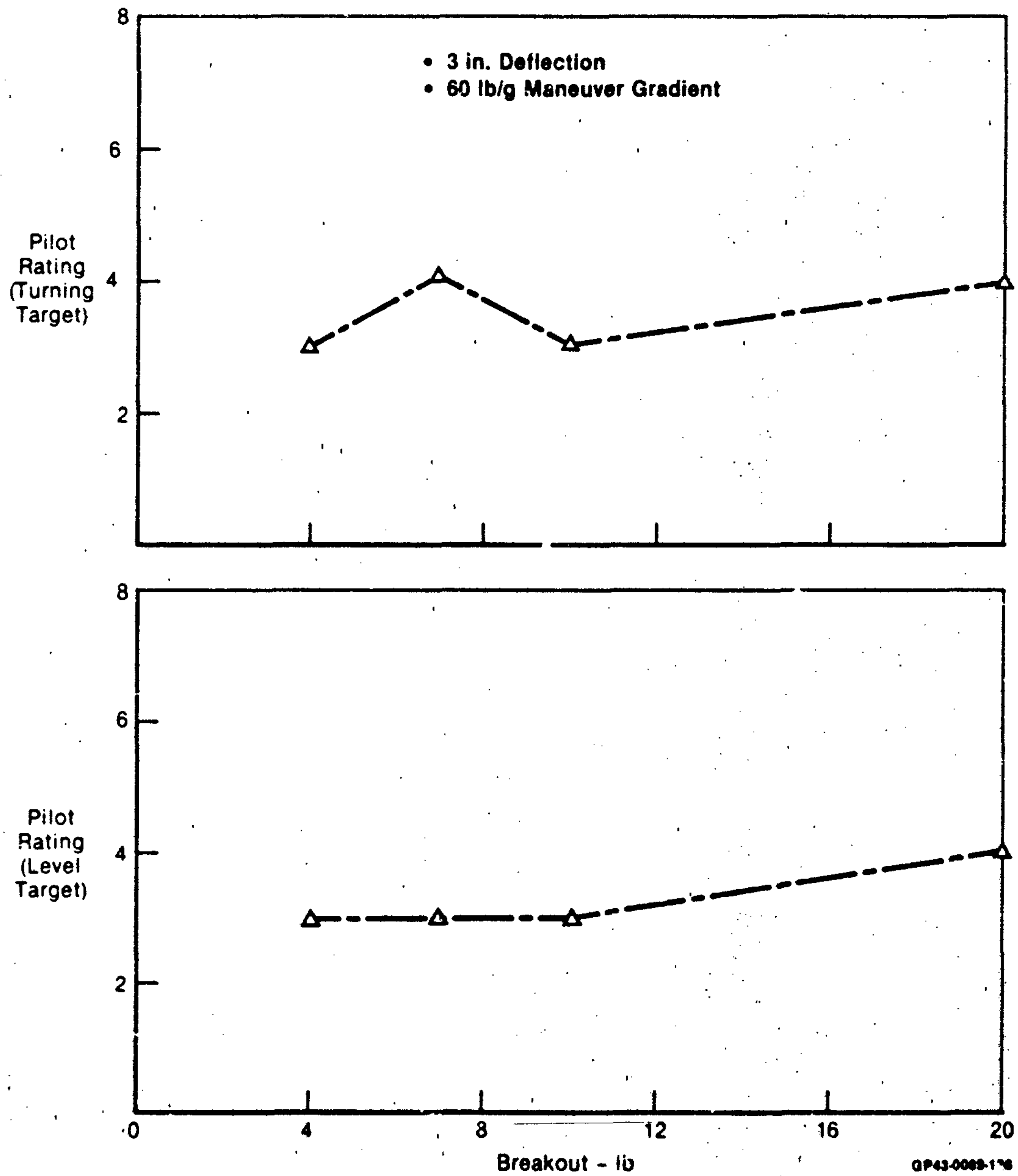

Figure 69. Pilot Rating vs Breakout
Rudder Pedals Wings Level Turn Pilot 23

Pilot 21's ratings for the breakout variation shown in Figure 68 indicated definite degradation in pilot rating for breakouts greater than 10 lb. The same trends appear in Pilot 23 evaluations but are emphasized more by examining his comments. The CH=4 shown for the 7 lb breakout case was from the first evaluation of the three inch deflection. His only negative comment was that he was a little slow getting on target. His comments on the 15 and 20 lb breakouts, however, indicate definite problems. For these configurations he found himself making many small reversing pedal inputs around neutral when following the target during bank angle reversals. Again, in his opinion, this was not severe enough to warrant increasing his ratings above a CH=4.

All three pilots examined the two inch pedal deflection configurations. By examining both the level and turning target data presented in Figure 69, it appears that the preferred maneuver gradient would be in the region near 40 lb/g. There are no apparent explanations for the large dispersions in Pilot 22's ratings as shown in this figure.

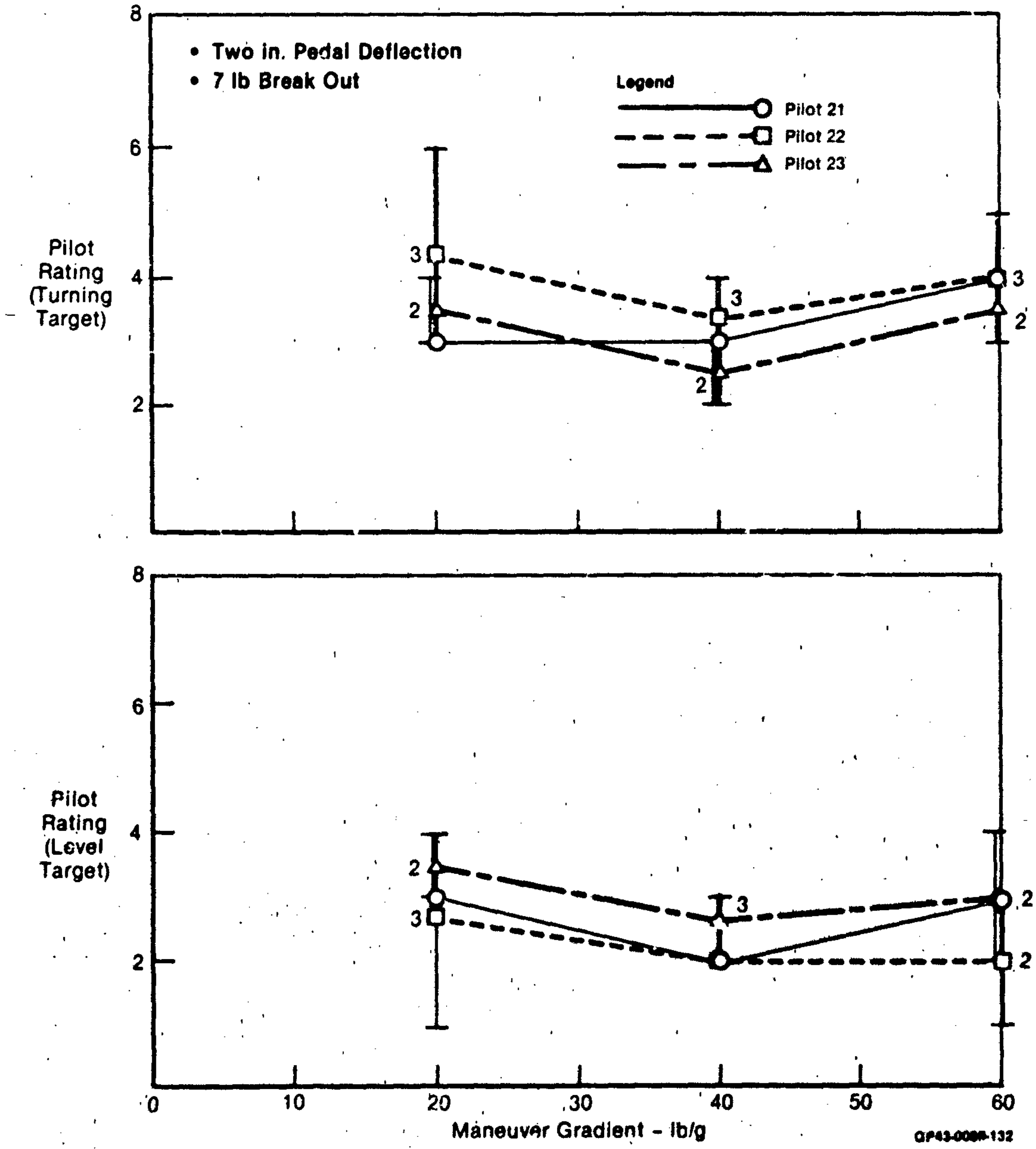

Figure 69. Pilot Rating vs Maneuver Gradient
Rudder Pedals Wings Level Turn

The level target breakout rating data shown in Figure 70 for Pilot 21 indicates a degradation of rating at a breakout value of 10 lb. For Pilot 22 the degradation begins at a breakout of 15 lb. The pilot ratings for the turning target task are somewhat confusing. The trends seem to indicate no real preference for breakout in the range of 4 to 15 lb examined by Pilots 21 and 22.

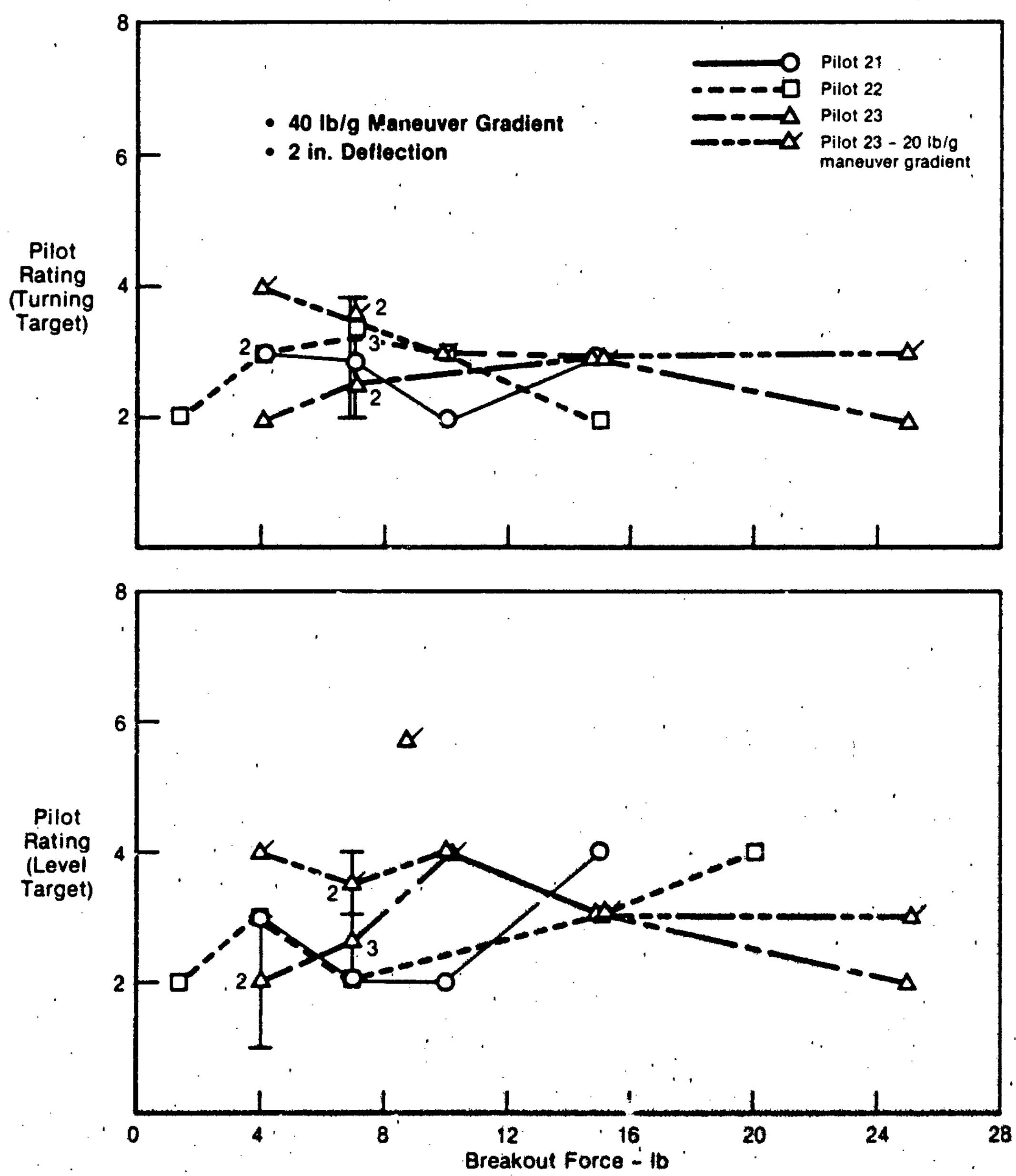

Figure 70. Pilot Rating vs Breakout Force
Rudder Pedals Wings Level Turn

Due to personal problems and to an unfortunate choice of maneuver gradient (see Vol. II for details), Pilot 23's ratings should be treated with skepticism.

The approach and landing tasks were flown using aircraft dynamics that would reasonably be expected for a STOL fighter. The environment consisted of a 15 knot headwind which sheared to a crosswind at touchdown. Moderate turbulence was used for all evaluations. Approach speed was 115 knots and 0.2 g of wings level turn authority was available.

Examination of the pilot ratings of Figures 71, 72, and 73 indicate a preference for rudder pedal maneuver gradients below the 300 pounds per g level with the optimum appearing to be between 100 and 200 lb/g. Additionally, Figure 71 indicates that one pilot did not like gradients below 75 pounds per g with the half inch maximum pedal deflection. No clear preference was indicated for the half inch, two inch, or three inch pedal deflection. One pilot felt one-half inch deflection more harmonious with limited sidestick motion. Another pilot felt prolonged use could result in "stiff legs". The three inch deflection pedals provided no problems but also no real benefits for Pilot 21. The data of Figures 74 and 75 generally show degradation in pilot rating for rudder pedal breakout forces above 7 pounds. A minimum acceptable breakout force was not observed.

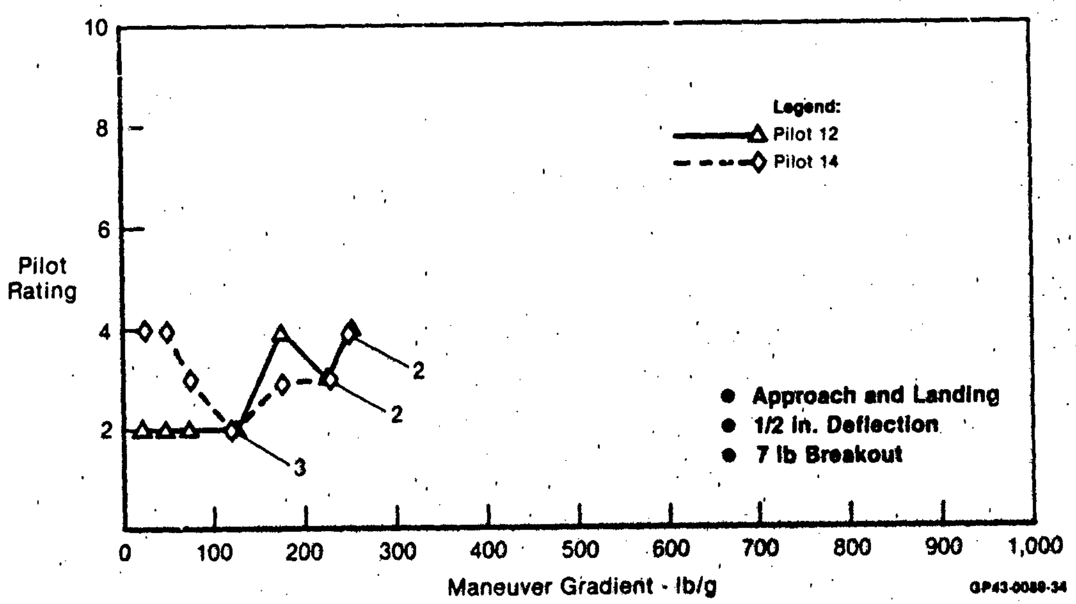

Figure 71. Pilot Rating vs Maneuver Gradient
Rudder Pedals Wings Level Turn

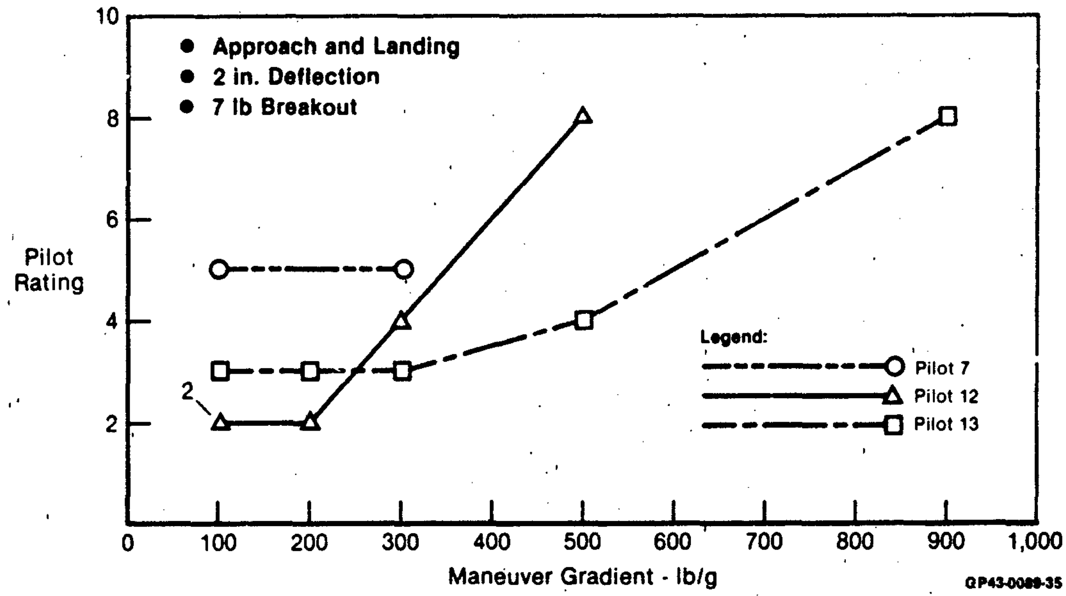

Figure 72. Pilot Rating vs Maneuver Gradient
Rudder Pedals Wings Level Turn

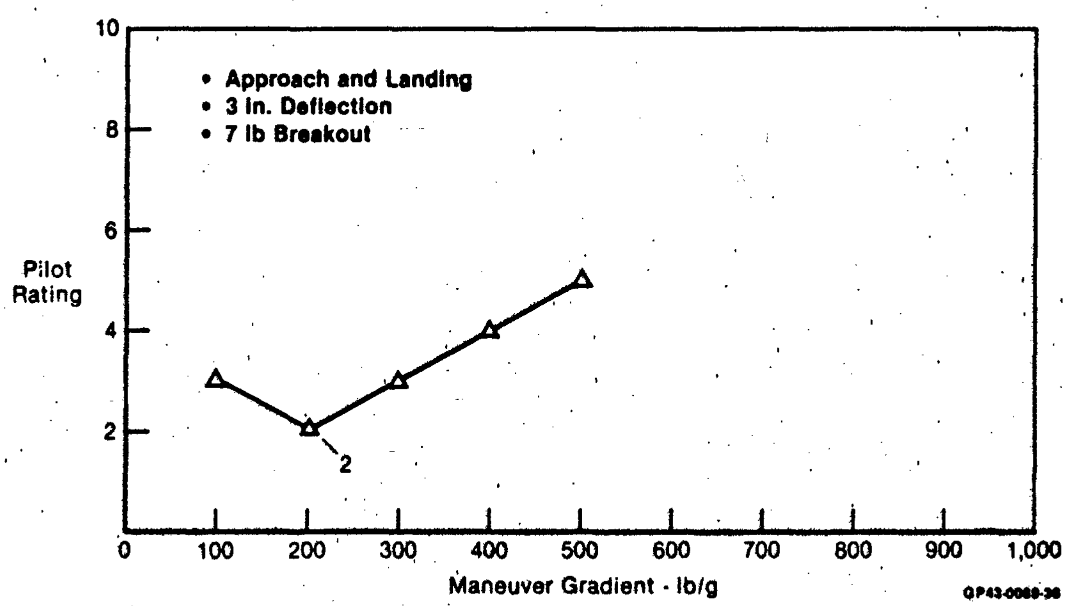

Figure 73. Pilot Rating vs Maneuver Gradient
Rudder Pedals Wings Level Turn Pilot 12

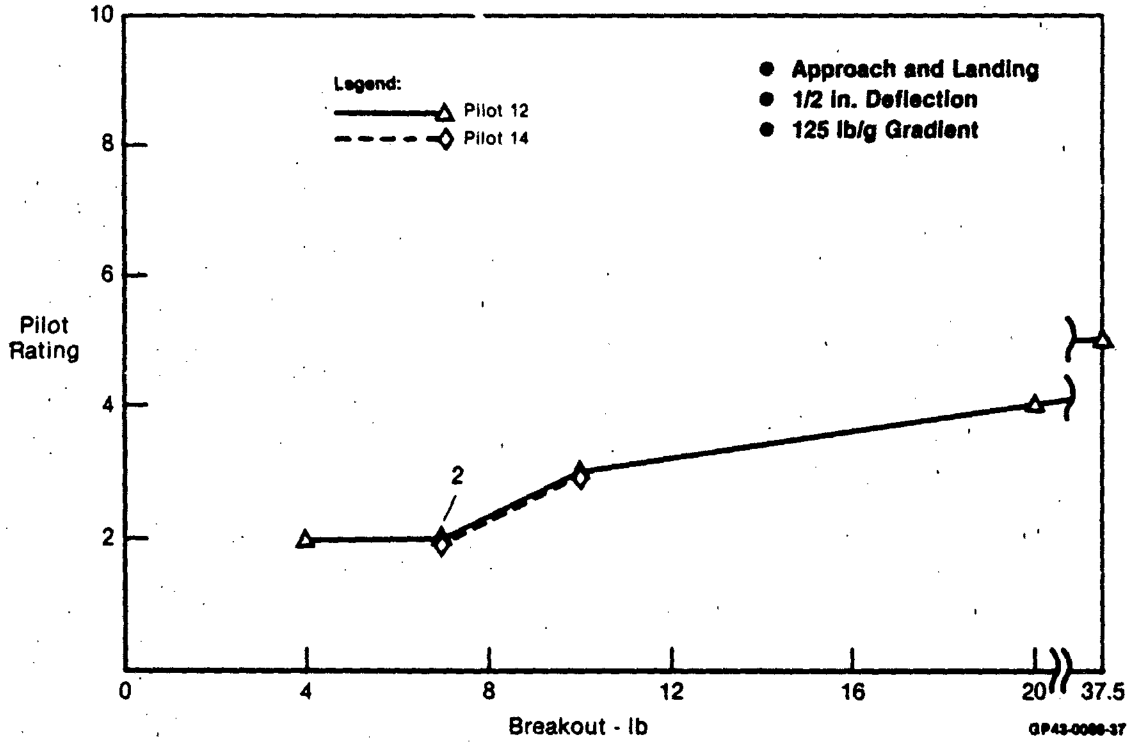

Figure 74. Pilot Rating vs Breakout
Rudder Pedals   Wings Level Turn

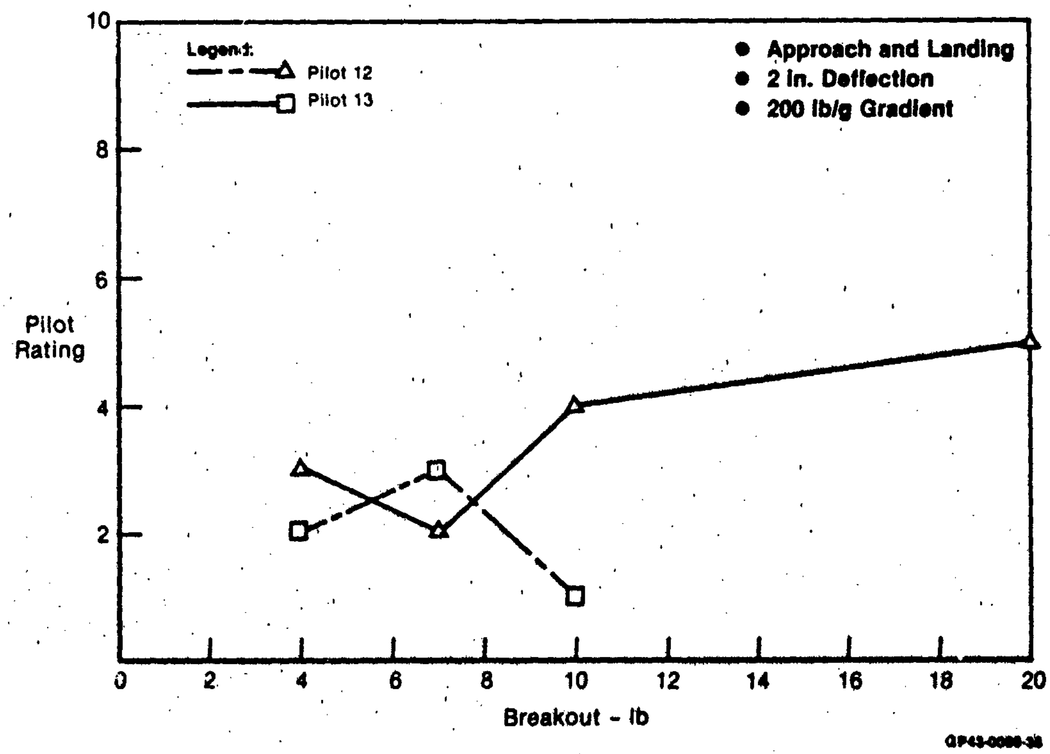

Figure 75. Pilot Rating vs Breakout
Rudder Pedals   Wings Level Turn

RUDDER PEDALS - WINGS LEVEL TURN MODE RECOMMENDATIONS: The recommended ranges of values for this requirement are:

Breakout	- between 1 and 7 pounds for Level 1 and 2
High speed maneuver gradients	- between 30 and 110 pounds per g
Low speed maneuver gradients	- between 100 and 200 pounds per g
Deflection	- between 1 and 2 inches

When attempting to recommend values for this controller, one is faced with a multitude of information. Some experiments were fixed-base simulations, others motion-base. There are even in-flight test results available. While there does appear to be some conflict in certain areas, some definite conclusions can be reached.

Breakout forces should be between 1 and 7 pounds for levels 1 and 2. This is the same requirement given for conventional rudder pedals in Reference 67, Section 3.5.2.1. These requirements are not included in Reference 68. In reviewing Reference 77, the following paragraph was noted concerning the specification of breakout forces:

> Although there are many indications that breakout forces should be a function of control force sensitivity (angular acceleration per pound of force) or some other force gradient, this approach was not used. The main reason for this is that there are not enough data (relating breakout forces and sensitivity) to justify the additional complication especially when measurement of breakout forces is usually quite imprecise anyway.

The results of the controller simulation support this statement. The results indicate there probably is a relationship between the optimum breakout force and a given maneuver gradient. As the maneuver gradient is decreased (i.e., becomes more sensitive) the effects of increasing breakout forces are more pronounced. The data supplied by the controller simulation are not sufficient to exactly specify this relationship. The data does support the requirements given above as a general range of acceptability. Design to meet this requirement, particularly the middle of the range, will insure the minimum impact of breakout force on pilot acceptance.

Control deflection is often a strong function of available cockpit space. With the trend to smaller, more compact crew stations, there is a tendency to decrease the amount of controller deflection to conserve space. The information in the qualitative requirement on control motion, supported by the controller simulation results tends to indicate this reduction may not be wise. Pilot comments from the controller simulation indicated that deflection between 1 and 2 inches was acceptable to all pilots. Smaller values received negative comments from at least one pilot in each task. Larger deflections resulted in neutral to negative comments from all pilots. If a limited displacement controller is used and lack of predictability in response is noted, increasing the controller deflection may provide some improvement.

Maneuver gradient correlations can be derived by comparing the results of three simulations. The results of Reference 44 define a recommended range of acceptable maneuver gradient as 20 to 110 pounds per g. The controller simulation and the simulations of References 44 and 52 appear to have found maneuver gradients in the region of 40 pounds per g at least acceptable (or nearly optimum) for high speed weapon delivery. Based on these observations, it is recommended that the lower limit be raised to 30 pounds per g. The simulation of Reference 42 used a lighter (i.e., more sensitive) gradient; however, not enough is known about the simulated response characteristics to make definite statements concerning the control sensitivity. The in-flight data from the YF-16 CCV program tends to indicate that 40 to 60 pounds per g may be slightly too sensitive for fine tracking. There are at least two possible reasons for this difference. One may be due to the differences between ground-based and in-flight testing such as noted for roll rate dynamics in Reference 75. Another, and equally likely cause, is the relatively high breakout forces used in that implementation (15 pounds). The results of the controller simulation indicate that such breakout forces can result in perceived sensitivity problems when operating about the neutral controller position. A detailed flight test program using an aircraft capable of operationally relevent response authorities (approx. 1 g minimum) would help to determine the exact cause. Note that from the discussion of the interrelationship between breakout force and maneuver gradient, increasing the maneuver gradient would probably tend to offset the effects of the breakout at the cost of increasing pilot force required for a given response.

The YF-16 CCV flight test results indicated a need for minimizing—the impact of flight condition changes on maneuver gradient (lb/g). This was included in the list of recommendations given in Reference 76. Such a system was mechanized for the controller simulation.

The controller simulation provided the only detailed data on characteristics for approach and landing. The recommendations for breakout and control deflection apply here as well. The recommended range of maneuver gradients is between 100 and 200 pounds per g. Two things drive the recommended gradient up as speed increases. One is the ability of the pilot to modulate his input using his feet. If a gradient of 40 pounds per g was used at a flight condition, where only 0.2 g's of authority was available, the pilot would have to modulate his inputs between zero and eight pounds above breakout. This is offset by the other effect, as speed decreases, yaw rate for a given lateral acceleration increases. An aircraft at 100 knots true airspeed with a maximum wings level turn authority of 0.2 g has the same yaw rate capability as an aircraft at 500 knots with a 1 g authority. Indeed, at low speeds and low authorities, it may be desirable to implement a constant pilot input per unit yaw rate maneuver gradient. As speed and authority decrease, the predominant cue sensed by the pilot probably changes from lateral acceleration to visible yaw rate.

Support for the recommended low speed maneuver gradient of 100 and 200 pounds comes from the in-flight simulation of Reference 26. While the simulation was structured to provide response data for high authority (2+ g) aircraft in an air-to-air tracking task, the true speed of the Navion (110 knots) compares favorably with the 115 knot approach speed used in the controller simulation. As noted, in the discussion, pilot opinion varied little with the pure modes when maneuver gradients of 125 pounds per g (.008 g/lb) and 250 pounds per g (.004 g/lb) were examined.

Future tactical aircraft may employ high authority (2+ g) wings level turn capability. The maneuver gradients discussed here have been linear gradients based on 1 g or less of available authority. This has been shown adequate for medium and five tracking inputs. However, such linear gradients would probably be undesirable for use in a high authority aircraft. Additionally, the inclusion of a digital computer in the flight control system allows the designer to tailor the maneuver gradient to enhance the mode's usefulness. A discussion of dual- and triple-slope sensitivities was included in Reference 76. Application of the fine and medium input given here combined with the capability of the digital computer should make such high authority aircraft easily manageable and useful.

TWIST GRIP CONTROLLER - WINGS LEVEL TURN MODE DISCUSSION: A twist grip control axis was incorporated in the sidestick used in the controller simulation. The pitch and roll axes of the sidestick had force-deflection gradients of approximately 40 pounds per inch with a maximum displacement of 0.4 inches at the grip center. The twist axis was perpendicular to the conventional pitch and roll axes. The twist force-deflection gradients were stiff enough that the pilots could not detect its presence when only conventional control responses were commanded from the sidestick. The mechanical characteristics of the twist axis included a force-deflection gradient of 12 inch-pounds of torque per degree of deflection with a 4 degree maximum deflection each side of neutral. No breakout force was provided. Hysteresis values were too small to be measured due to background noise in the simulation hardware.

The evaluation tasks for the twist grip were the same as those noted previously for the rudder pedals. These included air-to-ground strafing, air-to-air tracking, and approach and landing. The same evaluation pilots that evaluated the rudder pedals also evaluated the twist grip configurations.

Since this controller had no breakout force, a deadband was used to provide a neutral position for pilot reference. A baseline deadband of 0.48 in-lb was selected. The procedures used were identical to those used in the pedal evaluations. A maneuver gradient variation was conducted using the baseline deadband. A deadband variation was then conducted using the best manuever gradient. While it would have been ideal to conduct the deadband variations at the same maneuver gradient, pilot preference differed to an extent that this was not always possible.

The results of the maneuver gradient variations are presented in Figure 76. As indicated by the figure, pilot ratings for the lighter gradients differed significantly. However, at 36 inch-pounds per g, an acceptable pilot opinion rating area is indicated. The deadband variations are shown in Figure 77. There are insufficient data available to identify any clear trends in deadband values. Pilot opinion does appear to differ somewhat, however.

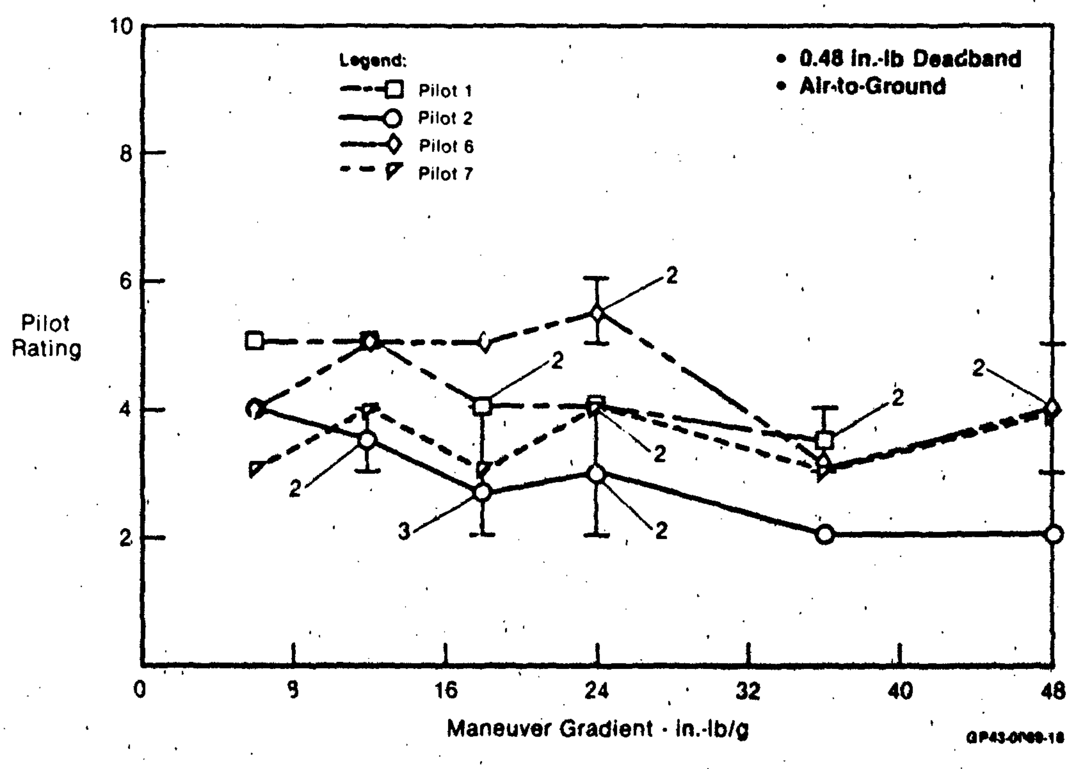

Figure 76. Pilot Rating vs Maneuvering Gradient
Twist Grip Sidestick Wings Level Turn

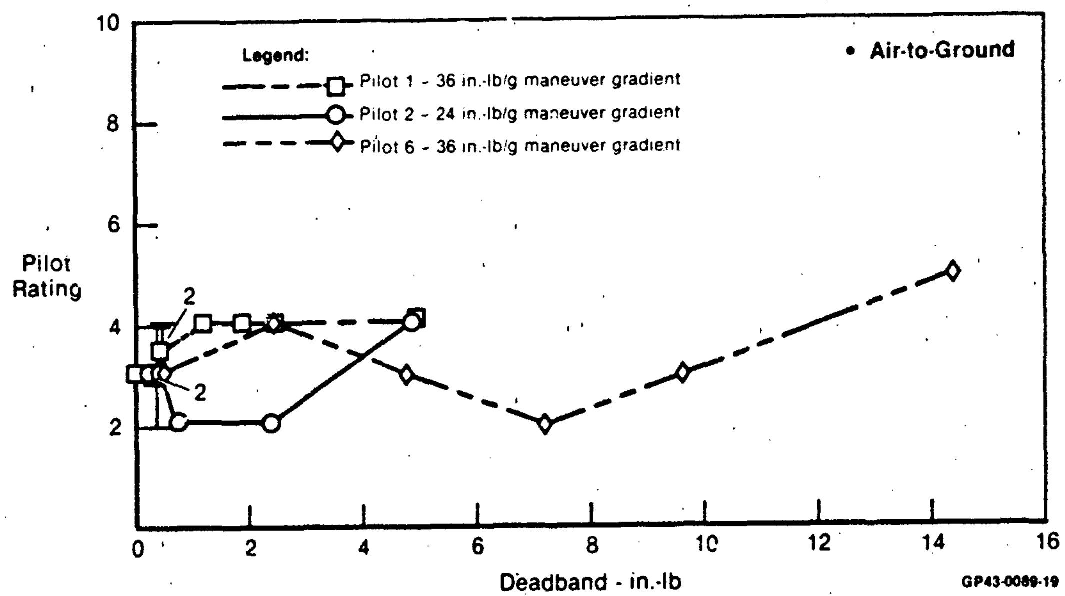

Figure 77. Pilot Rating vs Deadband
Twist Grip Sidestick Wings Level Turn

The amount of deadband necessary to prevent cross-axis coupling can be determined from the data obtained during the air-to-ground task. It became apparent from observing the runs and talking to the pilots during the debriefing that they tended to make corrections one axis at a time. Examination of cross plots of the pitch, roll, and wings level turn commands using rudder pedals confirmed this phenomenon. Examples are shown in Figures 78, 79 and 80. In Figure 78, the percent of roll rate command is plotted along the abscissa with percent wings level turn command plotted along the ordinate. This configuration was well liked by the pilot and received a CH=2 rating. Notice the almost total separation of control inputs. Figure 79 presents percent pitch command along the abscissa with percent wings level turn command as the ordinate. An almost total separation of control inputs is seen here also. In both these figures note that the wings level turn commands are between 40 and 60 percent of the 1g maximum. Roll rate versus pitch commands are shown in Figure 80. Again we see a separation of control inputs. It should be mentioned at this point that the pitch and roll axes had zero breakout and approximately 0.2 pounds of deadband.

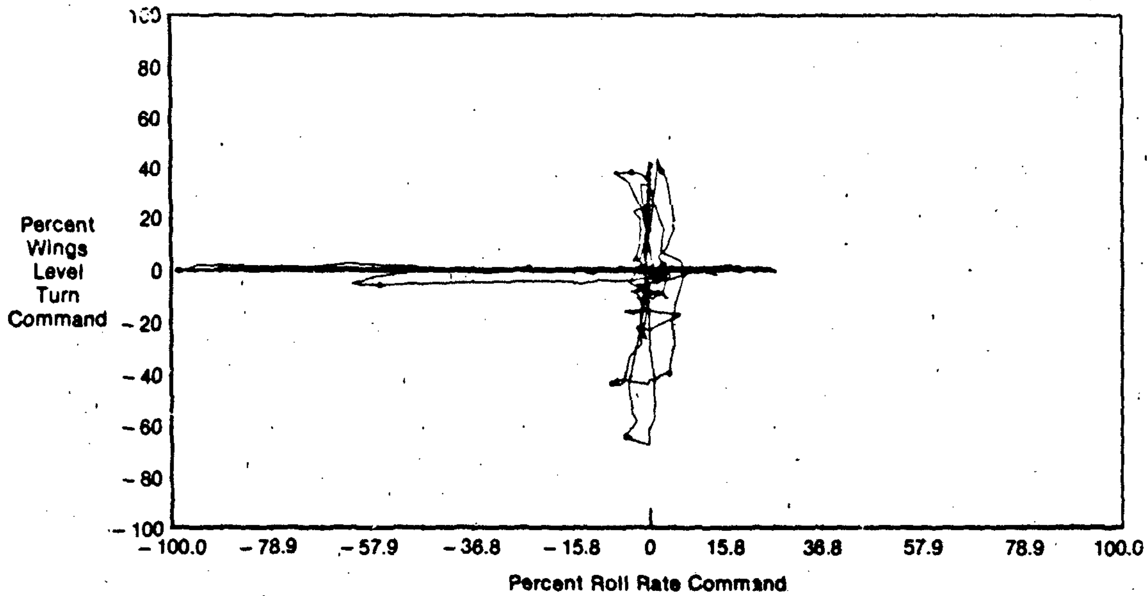

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Figure 78. Wings Level Turn Command vs Roll Rate Command
Rudder Pedals Percent of Maximum

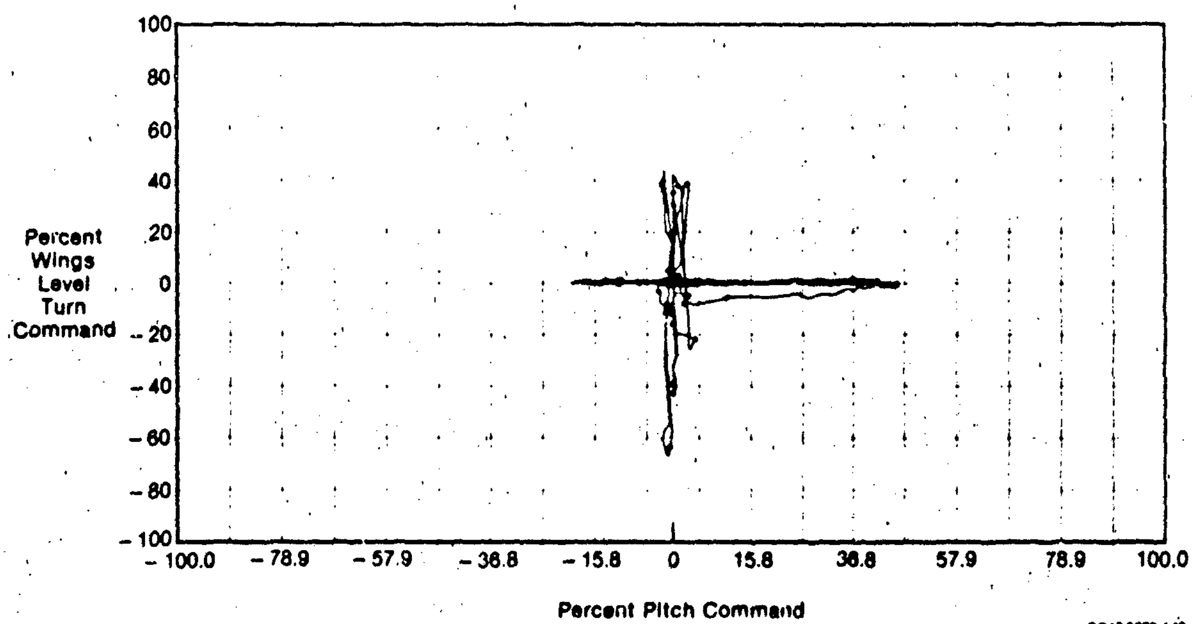

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Figure 79. Wings Level Turn Command vs Pitch Command
Rudder Pedals Percent of Maximum

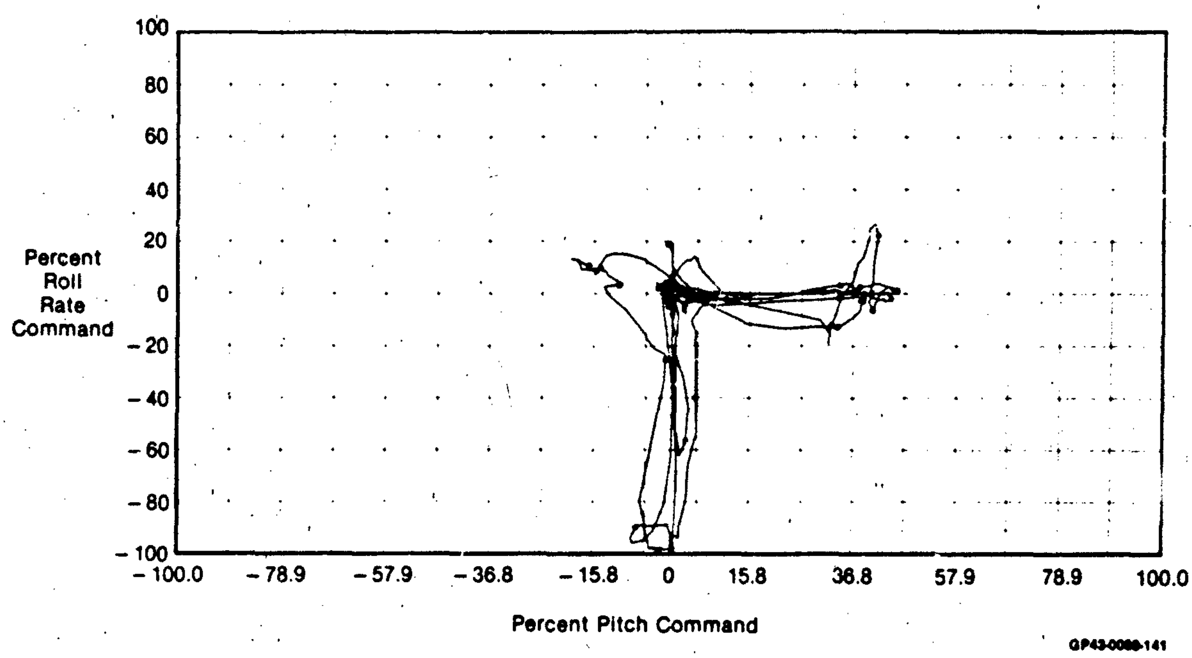

Figure 80. Roll Rate Command vs Pitch Command
Rudder Pedals Percent of Maximum

Examination of twist grip-wings level turn evaluations by the same pilot reveals coupling tendencies. Cross plots of percent wings level turn and roll rate commands are shown in Figure 81. Note the apparent cross-coupling in both axes and the reduced wings level turn command activity. At the maximum applied roll rate command, achieved during the roll portions of the pop-up maneuver, there is approximately a 20 percent wings level turn command. The pilot had very few negative comments about the configuration and assigned a CH=3 rating. It should be noted however that the wings level turn to roll rate coupling occurred at a time when the pilot did not have visual contact with the terrain board. Also note that the roll rate due to wings level turn command was between 5 percent and 15 percent of the maximum roll rate command.

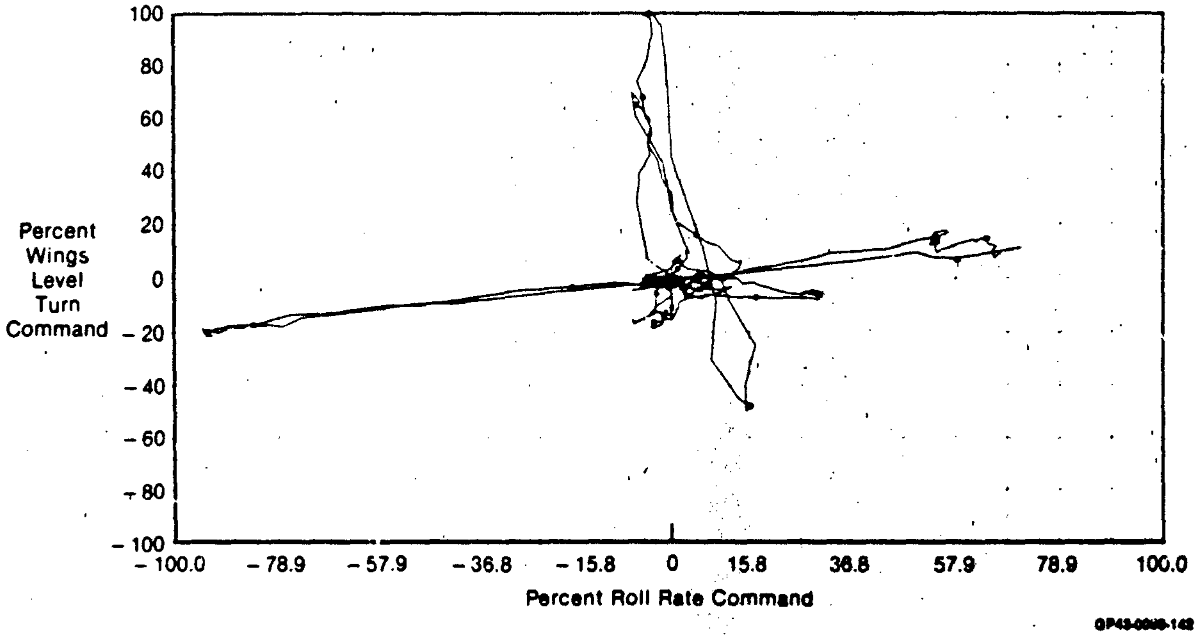

Figure 81. Wings Level Turn Command vs Roll Rate Command
Twist Grip Sidestick 0.48 In.-Lb Deadband Percent of Maximum

Based on the information presented in Figure 81, it appears that the wings level turn command to roll rate command coupling could be eliminated by increasing the twist grip deadband to approximately 7.5 in-lb of torque. Examination of Figure 82 indicates this is indeed the case. This configuration had a 7.2 in-lb deadband. Coupling of the roll rate command into the wings level turn command is eliminated except at the maximum roll rate command when the controller is on the left stop. The wings level turn command is between 60 and 90 percent of the maximum available. Compared with the rudder pedal inputs of Figure 78, it would appear that there is some coupling between wings level turn commands and roll rate commands. This coupling is, however, somewhat more difficult to quantify since these inputs are during the final target acquisition and tracking. It is also possible to precisely determine how much of the roll rate activity is due to coupling and how much is due to desired pilot inputs. Apparently the coupling was not too severe since the pilot assigned a CH=2 to this configuration.

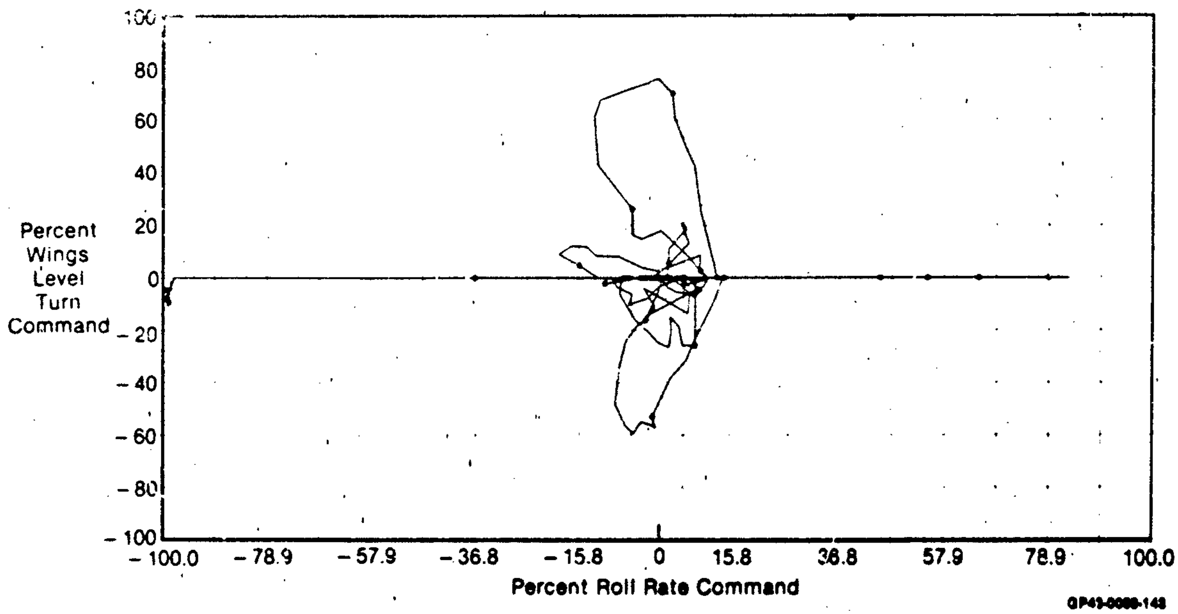

Figure 82. Wings Level Turn Command vs Roll Rate Command
Twist Grip Sidestick 7.2 In.-Lb Deadband Percent of Maximum

The maneuver gradient and deadband variations for the twist grip sidestick used for the air-to-air task are presented in Figures 83 and 84. It is obvious that Pilot 23 was much more sensitive to maneuver gradient variations than the other two pilots. Pilot 23 also found this controller to be easier to use in the turning target task. Based on the level target rating data it would appear the best results would be obtained using maneuver gradients between 24 and 36 inch-pounds per g. The data shown for Pilot 21 in Figure 84 indicates a definite degradation in pilot rating with increasing deadband. While the ratings show little or no effect for increasing deadband, a review of the pilot comments indicates a preference. With the increase in deadband beyond the baseline .48 in-lb used in the maneuver gradient variations, all pilots commented on the increased force required to achieve the desired response. They perceived it as an increase in maneuver gradient. At the 4.8 in-lb level, Pilot 21 complained of a delay in the response as well as an increase in required force. At this level, Pilot 23 felt that he was jerky on his control inputs and tended to overshoot the target. At the highest level tested, 7.5 in-lb, Pilot 21 complained that too much force was required and that there was not enough sensitivity in the level target task. In the turning target task he stated:

"It takes too much to get it going and then it's underdamped when it does go. You can't stop it and it wallows all over."

Pilot 23 commented at this point that he was twisting and getting nothing. In the case of the level target, he felt he could compensate and gave a CH=3. For the turning task he found he had to degrade to a CH=4. It should be noted that Pilot 21 used a lighter maneuver gradient than did 22 or 23. How much this influenced his sensitivity to the deadband is difficult to judge. It is consistent with the effect of breakout observed in the one inch deflection rudder pedals.

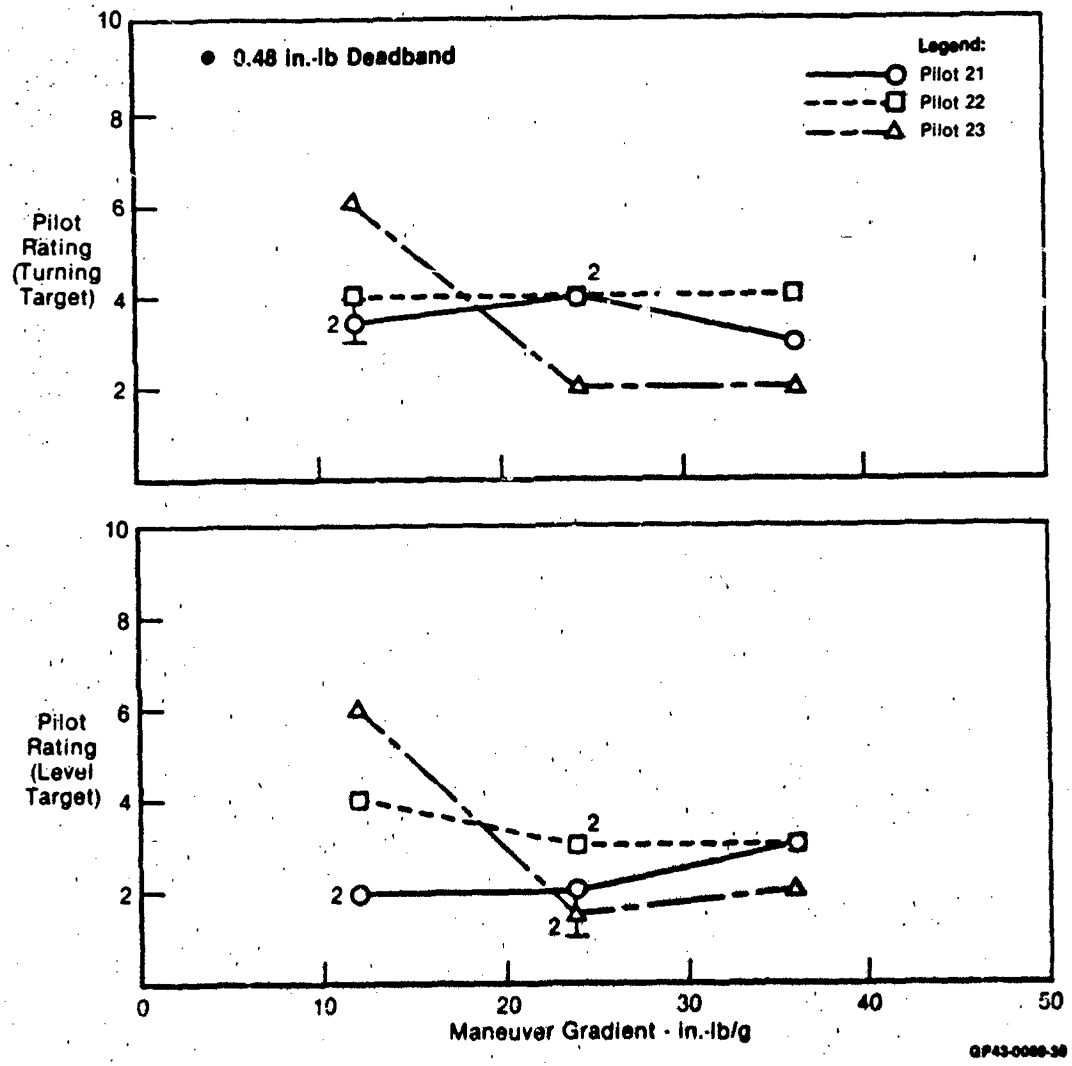

Figure 83. Pilot Rating vs Maneuver Gradient
Twist Grip Sidestick Wings Level Turn

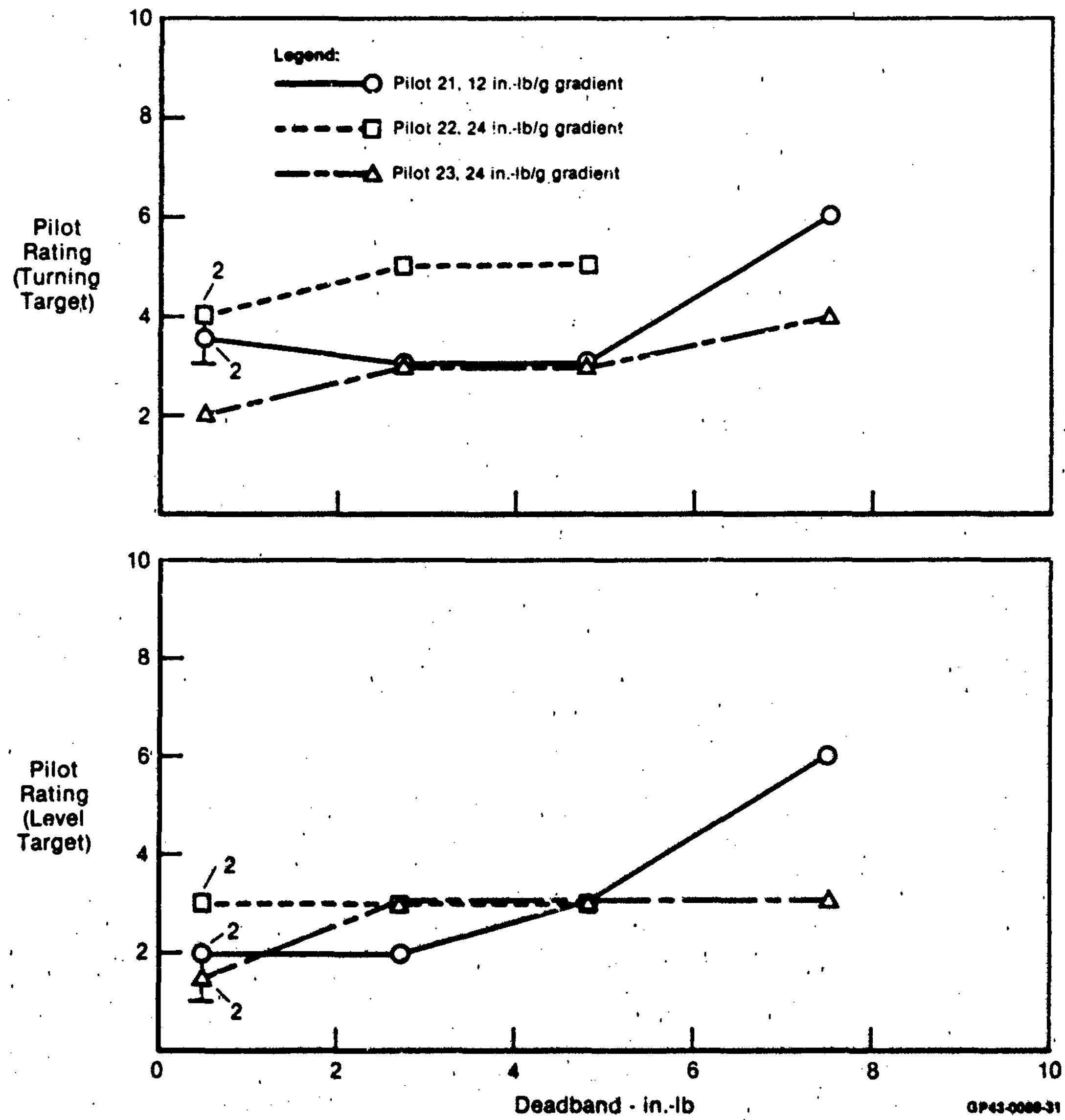

Figure 84. Pilot Rating vs Deadband
Twist Grip Sidestick Wings Level Turn

Pilots 22 and 23 had also participated in the air-to-ground evaluation where they were identified as Pilots 7 and 2 respectively. The comparison of Pilot 22's air-to-air and air-to-ground ratings for the maneuver gradient variation are shown in Figure 85. Note the similarity in ratings. The lack of trends of preference for a desired maneuver gradient are felt to be due to the pilot's view of the controller in general. The pilot never fully adapted to this controller and indicated it was his least favorite for the air-to-air tasks. Pilot 22 did not perform a deadband variation sweep in the air-to-ground tasks. The maneuver gradient comparison for Pilot 23, shown in Figure 86, indicates similar trends for both tasks. The apparent acceptability of lighter gradients in the air-to-ground task may be due to the nature of the task. Because of the requirement to translate quickly from one target to the next, pilot inputs in the air-to-ground tasks were often more rapid and of larger amplitude than for the air-to-air task. Pilot comments have indicated that a lighter maneuver gradient can result in a perceived quickening of the response, highly desirable for the air-to-ground task. The deadband comparisons are shown in Figure 87. The apparent increase in sensitivity to increasing deadband in the air-to-ground task is also felt to be related to the differences in task. For instance, at a deadband of 4.8 inch-pounds in the air-to-ground task, Pilot 23's comments indicate that the major problem was coupling of twist axis inputs into other control axes. These types of comments were not noted in the air-to-air evaluations.

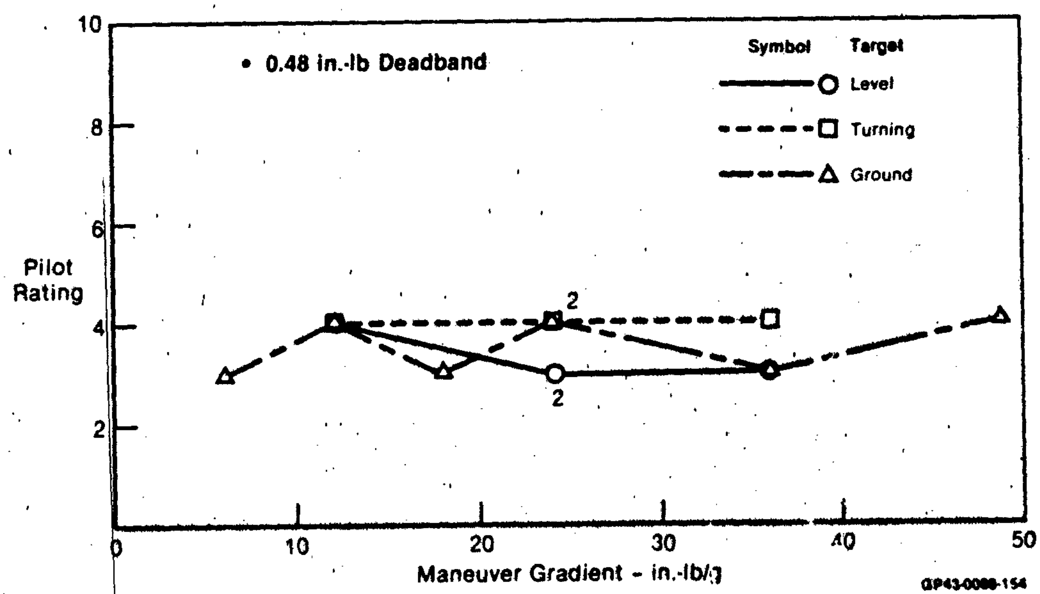

Figure 85. Pilot Rating vs Maneuver Gradient
Twist Grip Sidestick Wings Level Turn Pilot 22

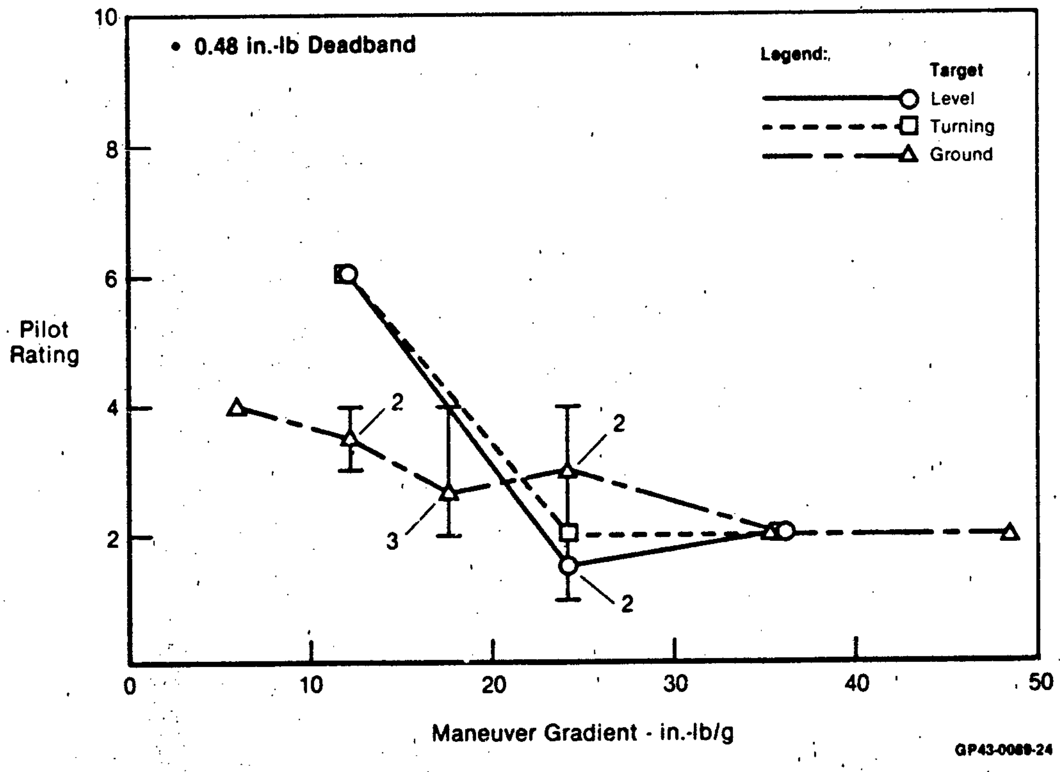

Figure 86. Pilot Rating vs Maneuver Gradient
Twist Grip Sidestick Wings Level Turn Pilot 23

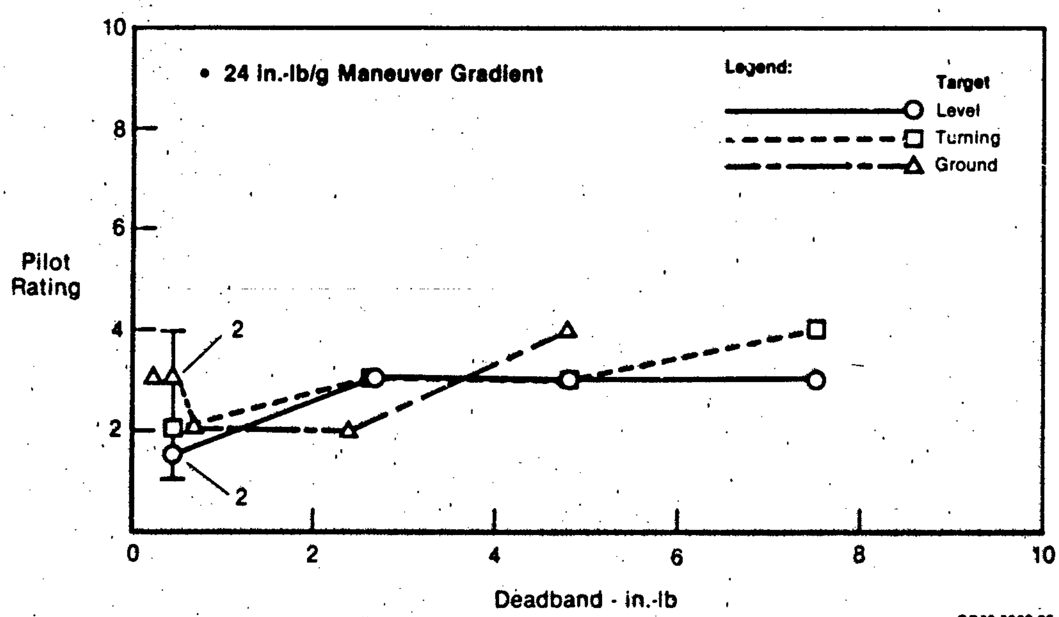

Figure 87. Pilot Rating vs Deadband
Twist Grip Sidestick Wings Level Turn Pilot 23

Also during the air-to-air evaluations, one pilot conducted a series of runs aimed at defining motion effects on pilot control input. The techniques, procedures and data are presented in Volume II. The results showed that although small deadbands (0.48 in-lb and 2.7 in-lb) were acceptable to the pilot, spectral analysis indicated motion feedthrough to the twist grip. At 4.8 inch-pounds, motion feedthrough was reduced however pilot rating declined to CH=4. At a deadband of 9.6 inch-pounds the pilot indicated a definite delay in the response. While no motion feedback was in evidence, definite crosscoupling between roll and wings level turn were indicated. These results indicate that while pilots in the simulation preferred very small deadbands, controllers with no breakout force may require some amount of deadband to minimize motion coupling effects. Excessive values of deadband can lead to negative pilot comments and also result in cross-axis coupling.

For the approach and landing task, review of Figures 88 and 89 indicates no clear pilot opinion on maneuver gradient or deadband for the twist grip/wings level turn combination. Pilot 12 did indicate a preference for the lower maneuver gradients. This preference was also indicated by the comments of Pilot 13, though it is not apparent in his ratings. Pilot 12 was not comfortable with the twist grip controller in any of the evaluations. Comments indicate a tendency to tighten up on the controller in order to make twist inputs. Additionally, since there was no hard stop to indicate saturation, the pilot found that in tight simulations he was applying excessive torque inputs to ensure he was receiving full response. This resulted in fatigue and difficulties in applying inputs in other axes.

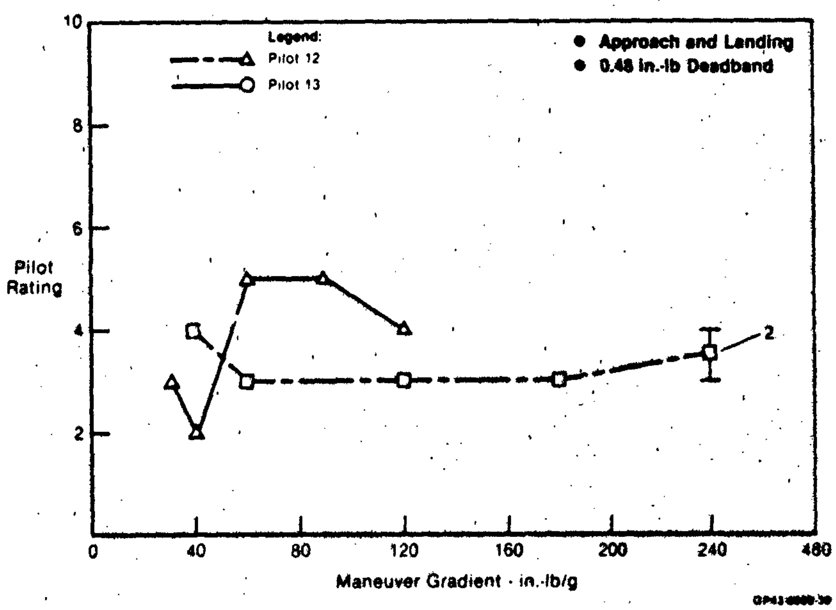

Figure 88. Pilot Rating vs Maneuver Gradient
Twist Grip Sidestick Wings Level Turn

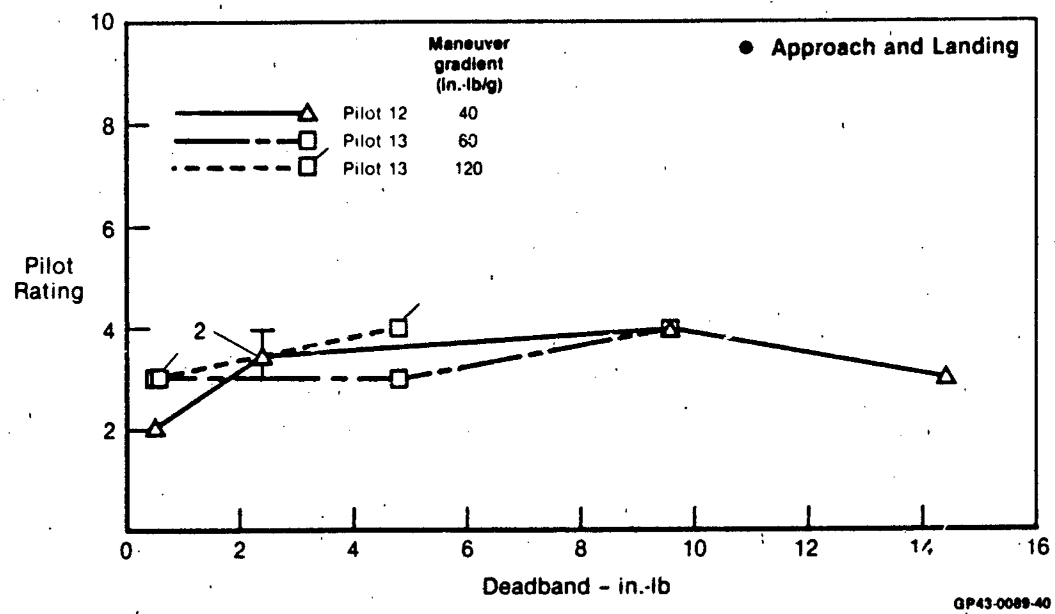

Figure 89. Pilot Rating vs Deadband
Twist Grip Sidestick   Wings Level Turn

TWIST GRIP CONTROLLER - WINGS LEVEL TURN MODE RECOMMENDATIONS: The following values have been identified as being potentially acceptable for this mode/controller combination:

Deadband	- 5 inch-pounds
High speed maneuver gradients	- 36 inch-pounds per g
Low speed maneuver gradients	- 120 inch-pounds per g
Deflection	- 8 degrees with solid stops

Note: Ranges of acceptable characteristics could not be determined.

As indicated in the discussion, the only data available for a twist grip controller incorporated in with conventional pitch and roll control comes from the controller simulation. Since the mechanical force-deflection gradient and breakout could not be changed, specific recommendations for gradient and deadband characteristics must be used with a certain degree of caution. As indicated in the rudder pedal requirement, controller force-deflection characteristics can have a strong impact on pilot opinion. No limits on acceptable characteristics can be determined from the above data, however values which have a high probability of being acceptable can be recommended.

Deflection characteristics for this type of controller should be increased above the 4 degrees available in the controller simulation. Based on pilot comments, approximately 8 degrees of rotation with hard stops indicating application of full input should be incorporated in future designs. The increased deflection would enhance the predictability of the response. The use of a hard stop combined with increased deflection would assist the pilot in determining when full control input had been applied. This would potentially reduce pilot fatigue and, as mentioned in the discussion, reduce coupling tendencies.

Deadband was shown to have potential uses beyond providing a definite neutral position. One use identified was to reduce cross-axis coupling from control inputs to the conventional flight control axes. The use of deadband was also shown as a means of reducing the effect of motion disturbances on pilot inputs. Deadband values should be as small as possible within the restrictions imposed by motion and cross-axis coupling effects. Similar to the effects noted for breakout, optimum deadband appears to be a strong function of maneuver gradient. An initial value of 4 inch-pounds is suggested. This value can then be modified dependent on its compatibility with the selected maneuver gradient.

Maneuver gradients should be selected to provide precise control and to minimize possible coupling effects. Based on the 1g authority and linear gradient used in the controller simulation, a value of 36 pounds per g is recommended for high speed tracking tasks. It is probably desirable to minimize gradient variation with flight condition. Although no data is available for this particular controller, since the gradient was held constant, information mentioned in the rudder pedal requirement indicates this may be beneficial or even necessary. Data for the approach and landing task is somewhat lacking. One pilot indicated a broad range of acceptable gradients, the other pilot never really adapted to the controller. A value of 120 inch-pounds per g is recommended based on the limited data.

While there is no requirement on grip shape, pilot comments indicate a square or elliptic cross-section would be preferable. This would facilitate the twisting action required. In addition the grip should be designed such that the vertical centerline is aligned with the twist axis in the region of the pilot's hand. This will help to minimize cross-axis coupling.

THUMB BUTTON CONTROLLER - WINGS LEVEL TURN MODE DISCUSSION: These devices have also been known as minature joysticks or isometric thumb buttons due to the limited displacement characteristics associated with these controllers. They are typically mounted in the center of the control stick grip. Controllers of this type were used in the studies of References 43, 46 and 53 for control of wings level turn. No data for controller characteristics or control mode results are presented in Reference 53 since that report concentrated on the use of blended and automatic uncoupled modes.

The largest bulk of data is available from the YF-16 CCV flight test program results of Reference 46. This controller was examined in the same tasks as the rudder pedals examined earlier. Maximum applicable force was 3.1 pounds with a deadband of 0.1 pounds. Exact values are not known, but if a maximum authority at full input of 0.8 g's is assumed, the maneuver gradient would be approximately 3.75 pounds per g. If a maximum authority of 0.4 g's were assumed, the resulting maneuver gradient would be 7.5 pounds per g. Based on the available information, these are representative of the air-to-ground and air-to-air maneuver gradients respectively. The maneuver gradients varied as a function of airspeed and normal load factor as discussed for the rudder pedals.

A review of the pilot comments in Reference 46 indicates that the button controller was used primarily to make "beep" type corrections. Some comments on abrupt response and control sensitivity were noted. A review of the run logs indicates little or no evaluation of the thumb button was conducted in the air-to-ground evaluations. Overall pilot opinion seemed to indicate the button was satisfactory for making small, rapid "beeping" corrections, however pedal control was preferable for large, continuous inputs. Additionally, in most instances, the button was used as a two axis controller with a longitudinal mode on the up-down axis and wings level turn on the left-right axis. Some cross-axis coupling was noted. A roll attitude autopilot was also used in alleviating pilot work load in the roll axis when using wing level turn.

A thumb button mounted on a sidestick was also evaluated in the controller simulation. The same evaluation tasks and pilots used in the rudder pedal and twist grip evaluations were used for this controller. The button used was capable of accepting up to a five pound input. Button motion was so slight that the controller appeared isometric to the pilot. The controller was used as a single axis device with only left-right inputs.

The pilot rating results of the maneuver gradient and deadband variations are presented in Figures 90 and 91. In reviewing Figure 90, it is apparent that two pilots felt they could use the controller effectively and the other two pilots could not. The thumb button was the least favored controller examined in this task. Only pilots 6 and 7 performed deadband variations for this

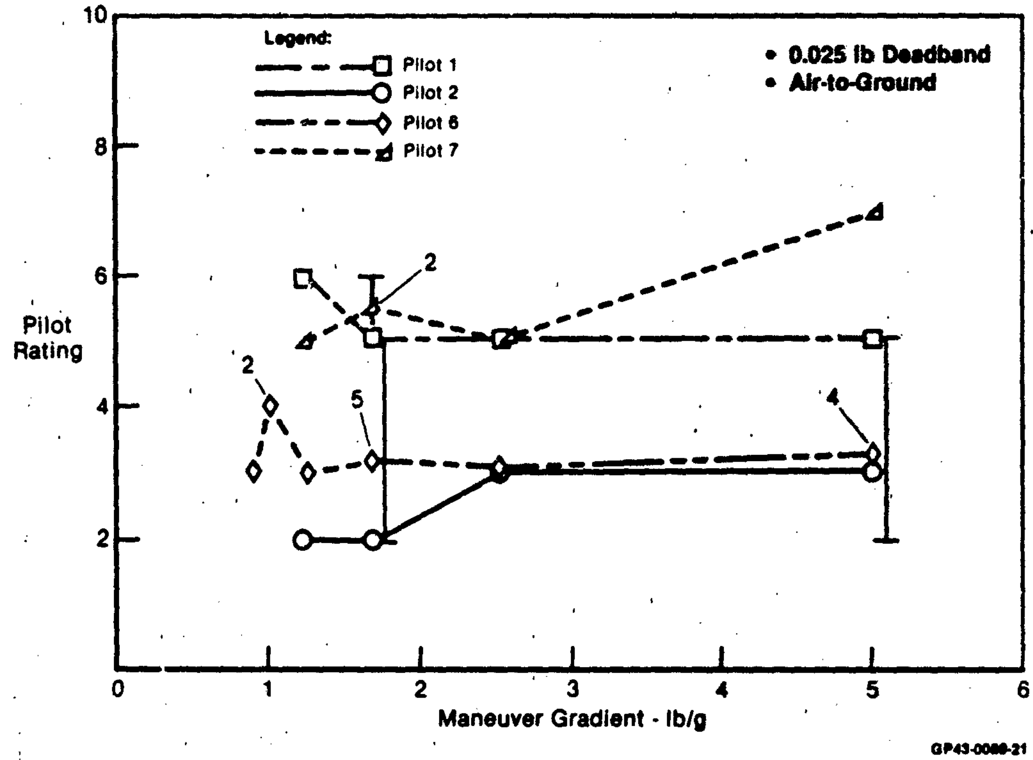

Figure 90. Pilot Rating vs Maneuver Gradient
Thumb Button Controller Wings Level Turn

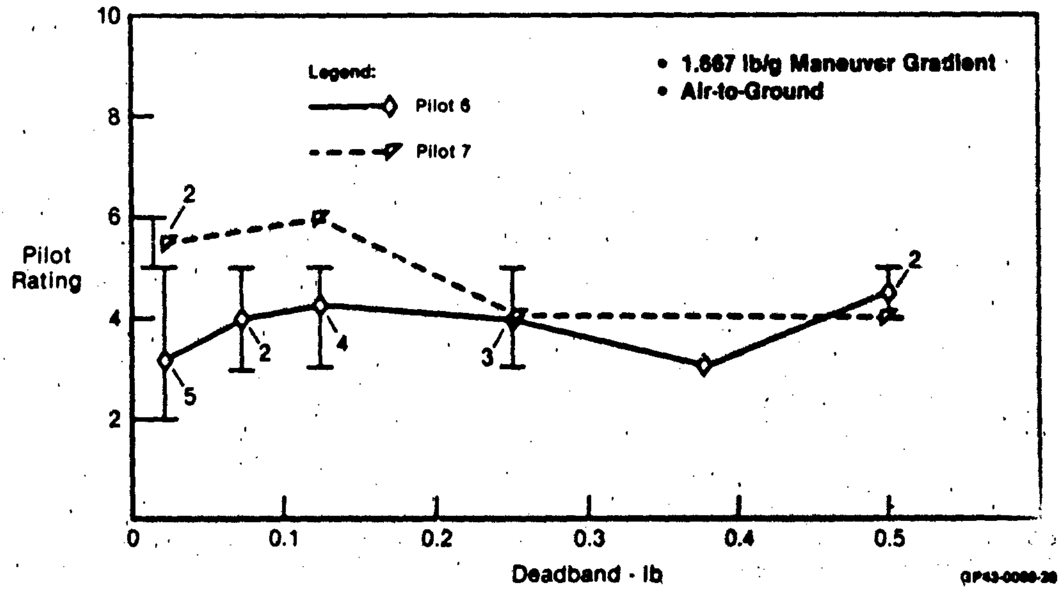

Figure 91. Pilot Rating vs Deadband
Thumb Button Controller Wings Level Turn

controller. It is interesting to note that while increasing deadband had a generally negative effect on Pilot 6's ratings, the increased deadband actually improved Pilot 7's ratings.

Pilot technique changed when using the thumb button controller. Pilot 6 found that he had difficulty making button inputs without coupling into the roll axis. For this reason he appears to have modified his control technique to using discrete button inputs and estimating the amount of lead to stop the gun cross on the target. This technique is indicated by the following excerpt taken from the voice tapes recorded during the simulation.

> Well, I've been using it more as an on/off, bang-bang type controller than anything else. I assume these are 300 foot wide runways here. If you are just going between two sides of the runways you don't need the full command authority. I don't think I've been using full command authority, but to get it onto the target initially, it's just full deflection until it's about maybe 100 feet away and then I cut the controller and let it drift over there and settle down on the target.

This technique is graphically illustrated in Figure 92. As would be expected, there is no apparent coupling between roll rate commands and wings level turn commands. However, it is apparent that roll rate commands are present during the wings

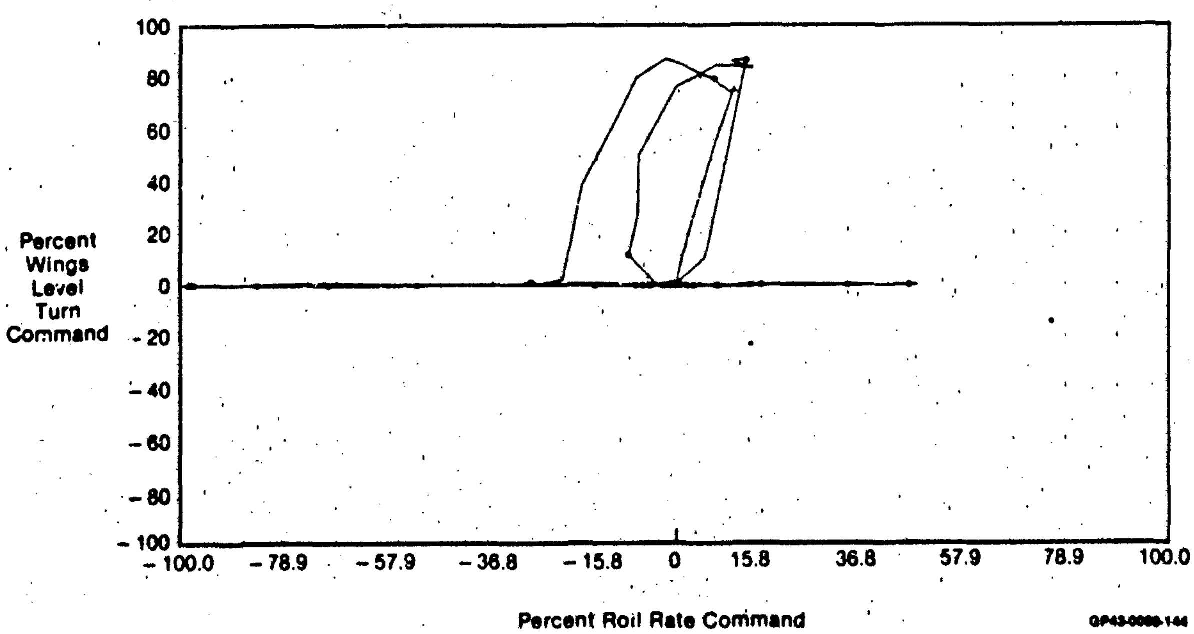

Figure 92. Wings Level Turn Command vs Roll Rate Command
Thumb Button Controller Percent of Maximum

level turn inputs. Notice also that there are only two high authority wings level turn commands. From Figure 93, it appears that the wings level turn commands also couple into the pitch axis. It is difficult to say that these pitch and roll inputs are definitely due exclusively to coupling since these inputs occur during target acquisition and tracking, although based on the pilot comments the probabilities are quite high that this is the case. The increased combined axis inputs shown in Figure 94 lead the observer to believe that the pilot is using more of the conventional response to solve the tracking problem than he had with other controllers. The button was configured with a 5.0 pound per g maneuver gradient and a 0.025 pound deadband. The pilot assigned the configuration a CH=3.

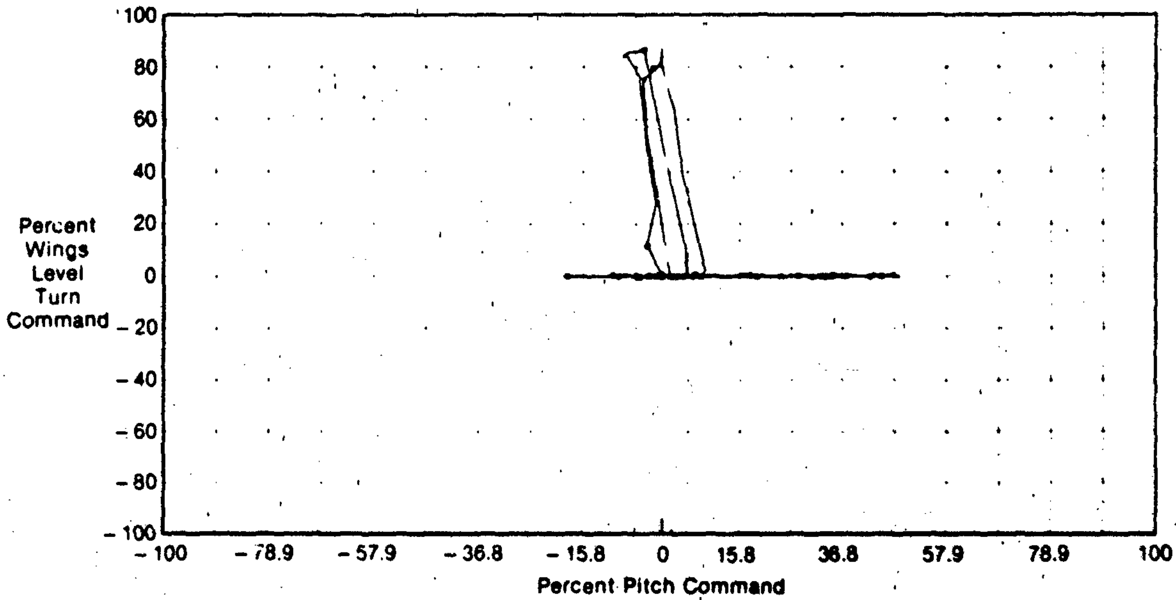

Figure 93. Wings Level Turn Command vs Pitch Command
Thumb Button Controller Percent of Maximum

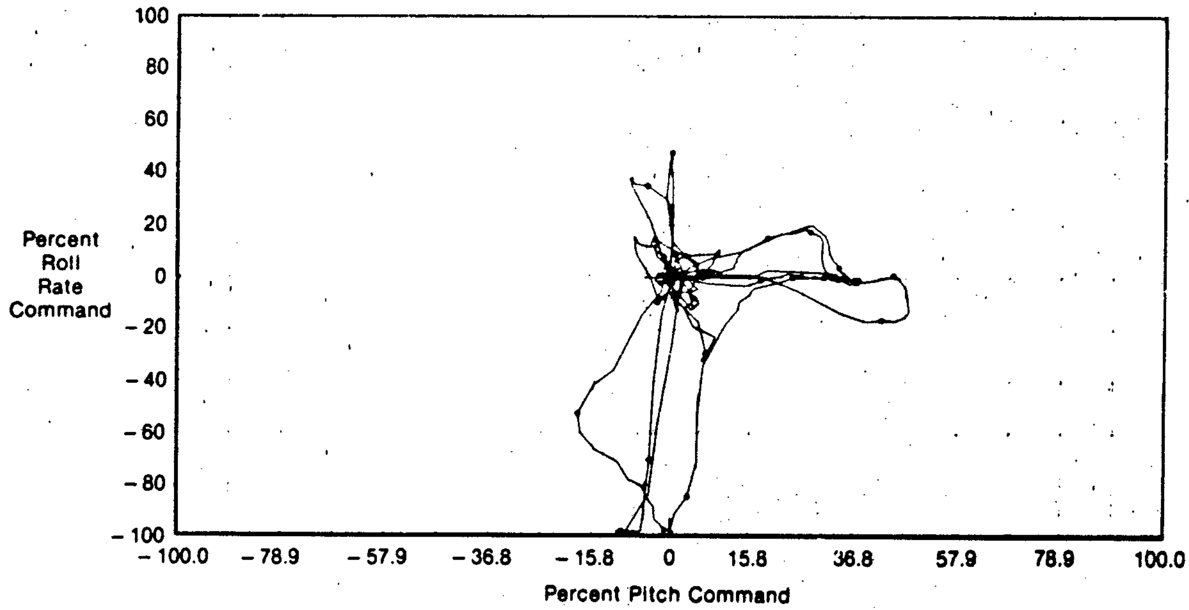

Figure 94. Roll Rate Command vs Pitch Command
Thumb Button Controller Percent of Maximum

The maneuver gradient and deadband variations for the thumb controller are presented in Figures 95 and 96. All the pilots were sensitive to variations in maneuver gradient. At the 1.25 lb/g gradient in the level target task, Pilot 23 entered a large amplitude pilot induced oscillation (PIO) that forced him to release the button and re-acquire the target using conventional control before continuing the evaluation. For Pilots 21 and 22, the 3.33 lb/g gradient seemed to work best and was selected for use in the deadband variations. Pilot 23 preferred the 5.0 lb/g gradient. He evaluated the deadband variations using the 3.33 lb/g gradient in both tasks and also the 5.0 lb/g gradient in the level target task. Increasing deadband seems to have had little effect on pilot rating; indeed, values of 0.5 and 1.0 lb resulted in slight improvements in some cases. It is believed these may be attributed to learning effects as much as anything else. It is interesting to note that using the 5 lb/g gradient, each pound of breakout reduced Pilot 23 maximum authority by 20%. At the 1.5 lb level he could command only 0.7 g of wings level turn. This appears to have had no effect on his accomplishment of the task. The major comment associated with the increase in deadband was an increase in force required to reach the desired response.

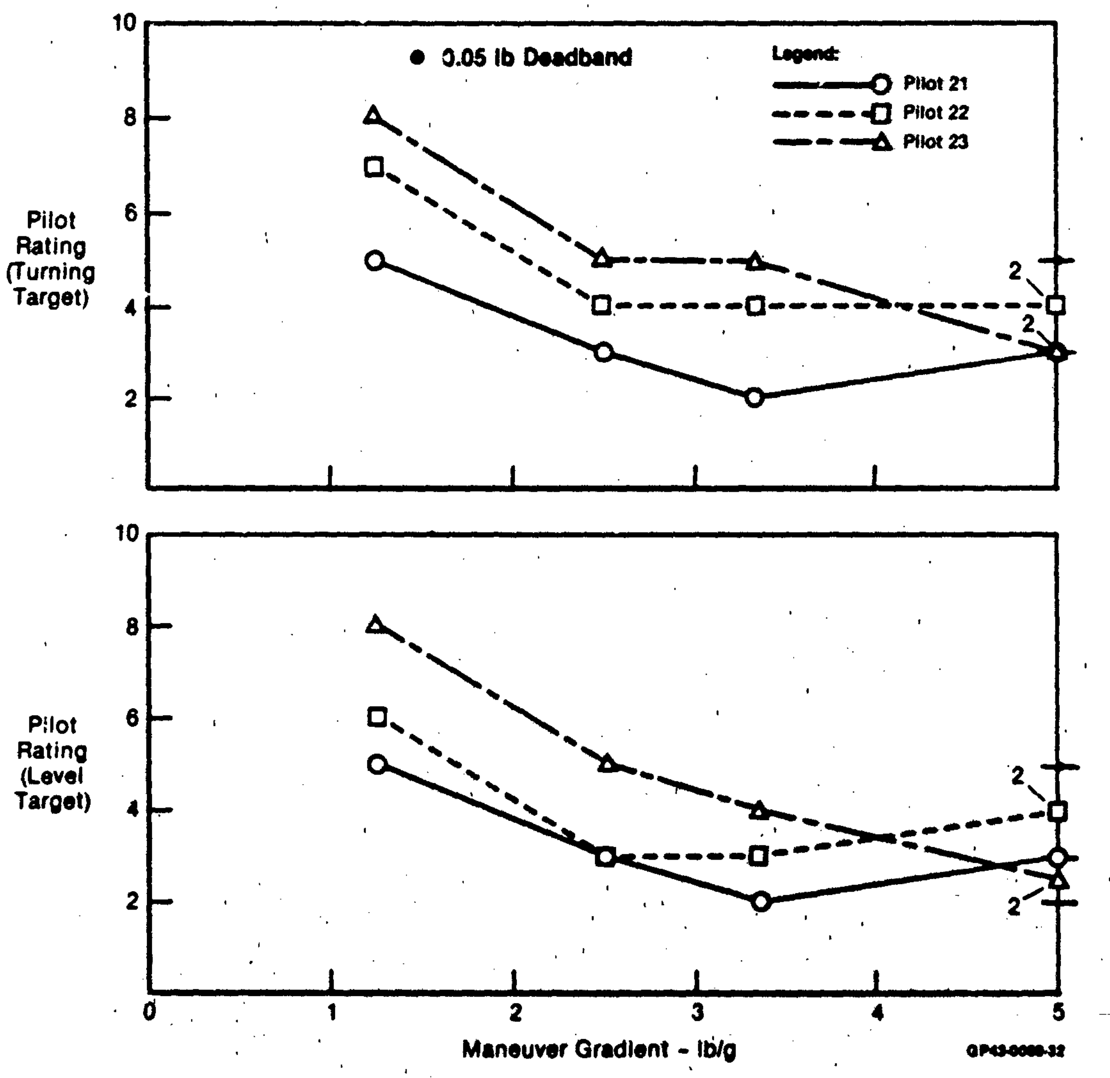

Figure 95. Pilot Rating vs Maneuver Gradient
Thumb Button Controller   Wings Level Turn

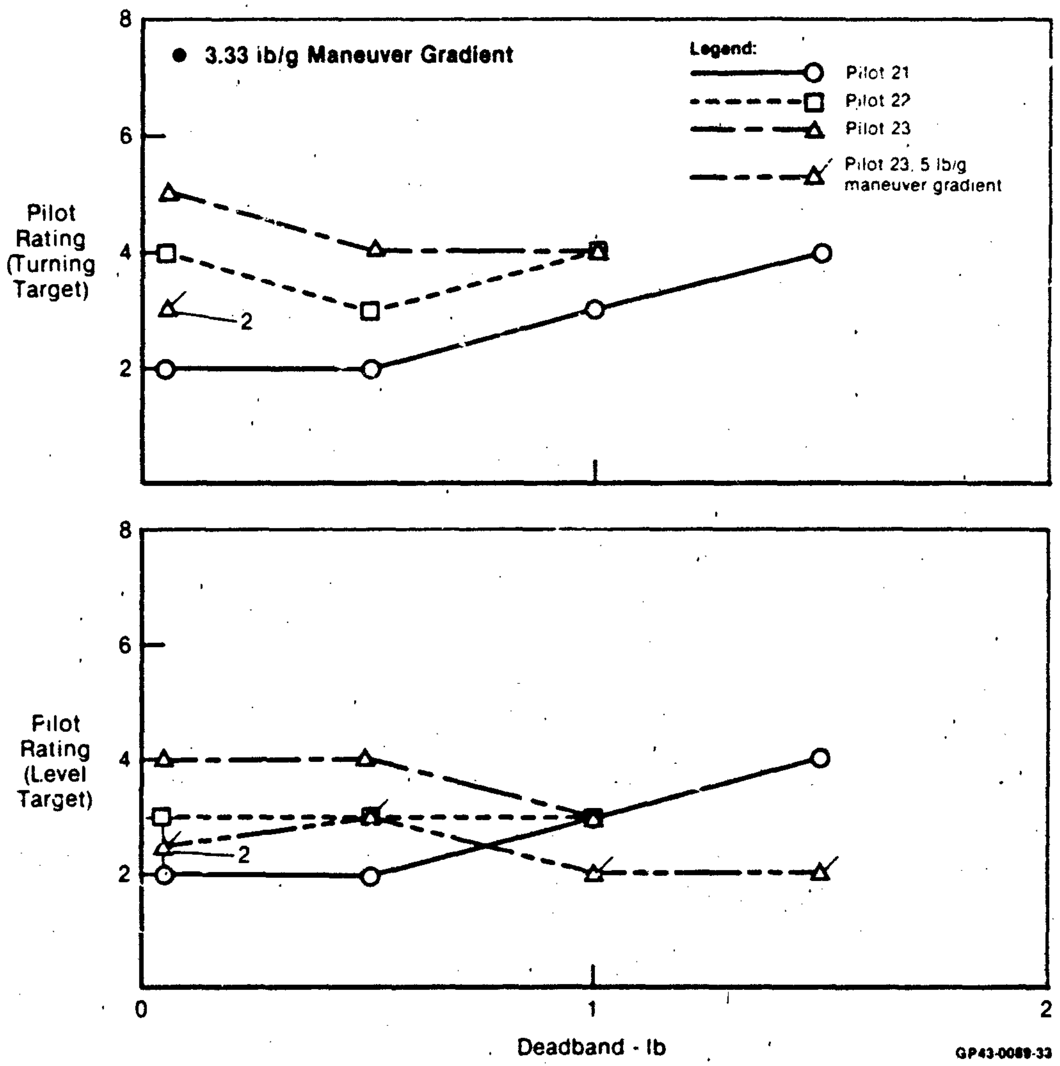

Figure 96. Pilot Rating vs Deadband
Thumb Button Controller Wings Level Turn

As indicated in the twist grip discussion, both Pilot 22 and 23 participated in the air-to-ground and air-to-air evaluations. The thumb button was Pilot 22's least favorite controller. The apparent reversal in trend for preferred maneuver gradient shown in Figure 97 is believed to be due to the difference in the tasks. The multiple target air-to-ground task required large, rapid inputs to transition between targets while the air-to-air tasks required continuous fine inputs. In the air-to-ground task, the pilot experienced severe coupling problems into the roll axis when testing the higher maneuver gradients. These same gradients resulted in improved pilot ratings in the air-to-air tasks. The comparison of the deadband variations are shown in Figure 98. Due to the difference in preferred maneuver gradient, no strong conclusions can be made. This problem is compounded by the limited range of deadbands examined by Pilot 22 in the air-to-ground evaluations.

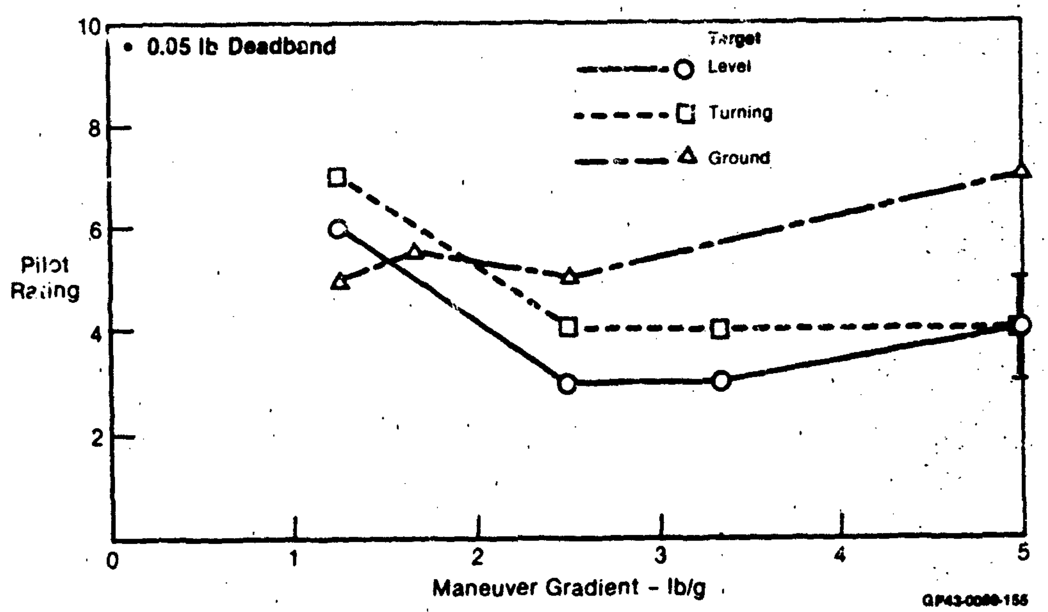

Figure 97. Pilot Rating vs Maneuver Gradient
Thumb Button Controller Wings Level Turn Pilot 22

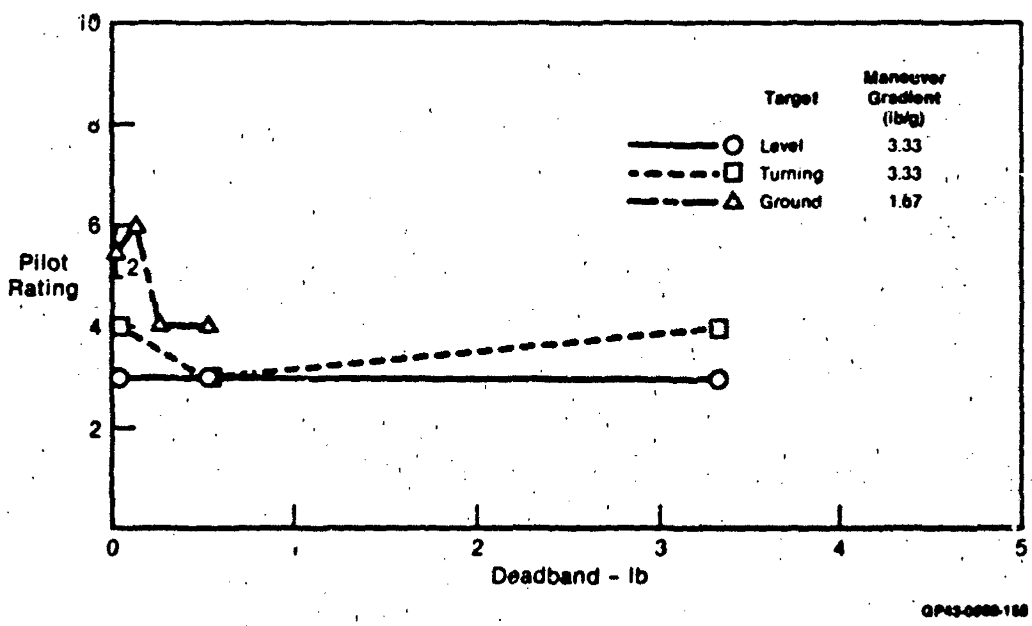

Figure 98. Pilot Rating vs Deadband
Thumb Button Controller Wings Level Turn Pilot 22

Figure 99 indicates the same trend in preferred thumb button maneuver gradient for Pilot 23 as was noted for Pilot 22. However, Pilot 23 found the button to be more acceptable in the air-to-ground tasks than did Pilot 22. The difference in rating for the lighter maneuver gradients shown in the figure is felt to be consistent with the sharp, high authority usage previously described for mode usage in the air-to-ground tasks.

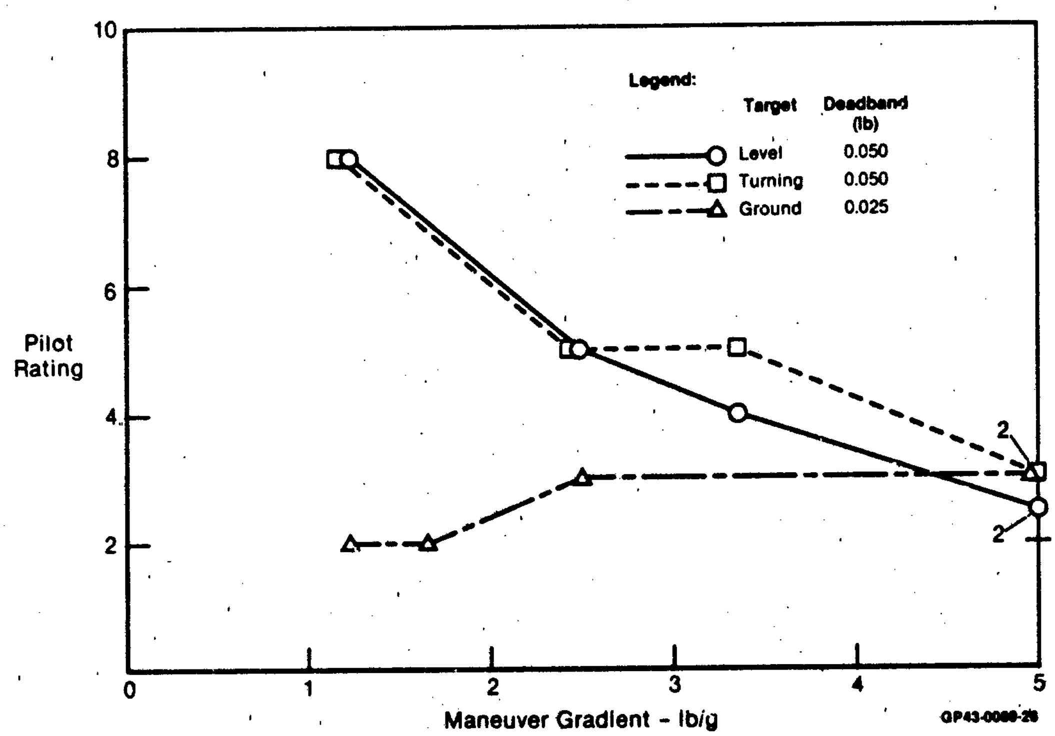

Figure 99. Pilot Rating vs Maneuver Gradient
Thumb Button Controller Wings Level Turn Pilot 23

The approach and landing task was described previously for the pedals and twist grip. Figures 100 and 101 indicate some preference by Pilot 12 for the lower maneuver gradients and deadbands. It is interesting to note that at the 5 pound per g gradient, a one pound force applied by the pilot results in full command. Coupling this with the fact that a 0.75 lb deadband resulted in a pilot rating of 4 may indicate that the pilot is not executing fine control inputs. Instead there appears to be a tendency to use on-off, "beep" type control inputs. Review of the pilot comments indicated this on-off control strategy was used with the more sensitive grip and thumb controller configurations in this task.

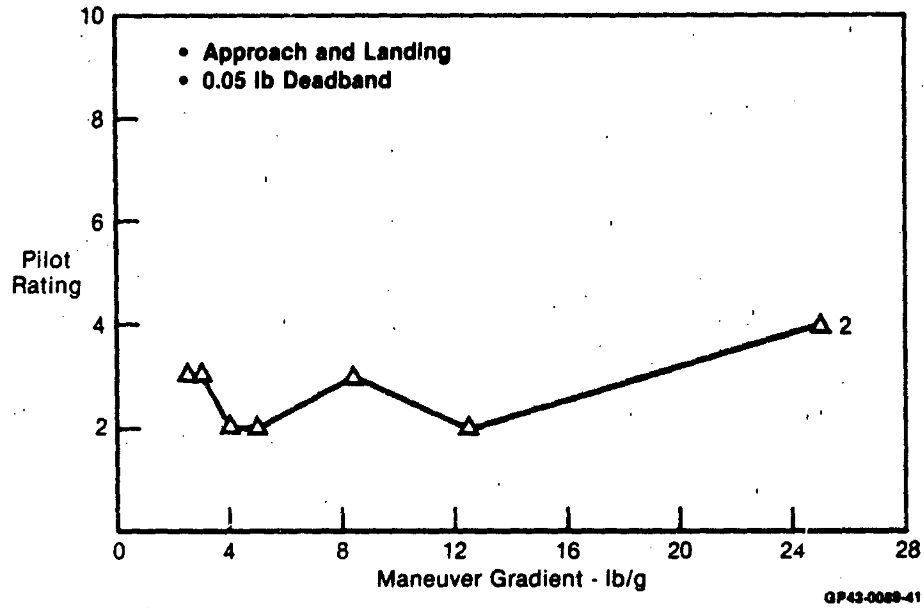

Figure 100. Pilot Rating vs Maneuver Gradient
Thumb Button Controller   Wings Level Turn   Pilot 12

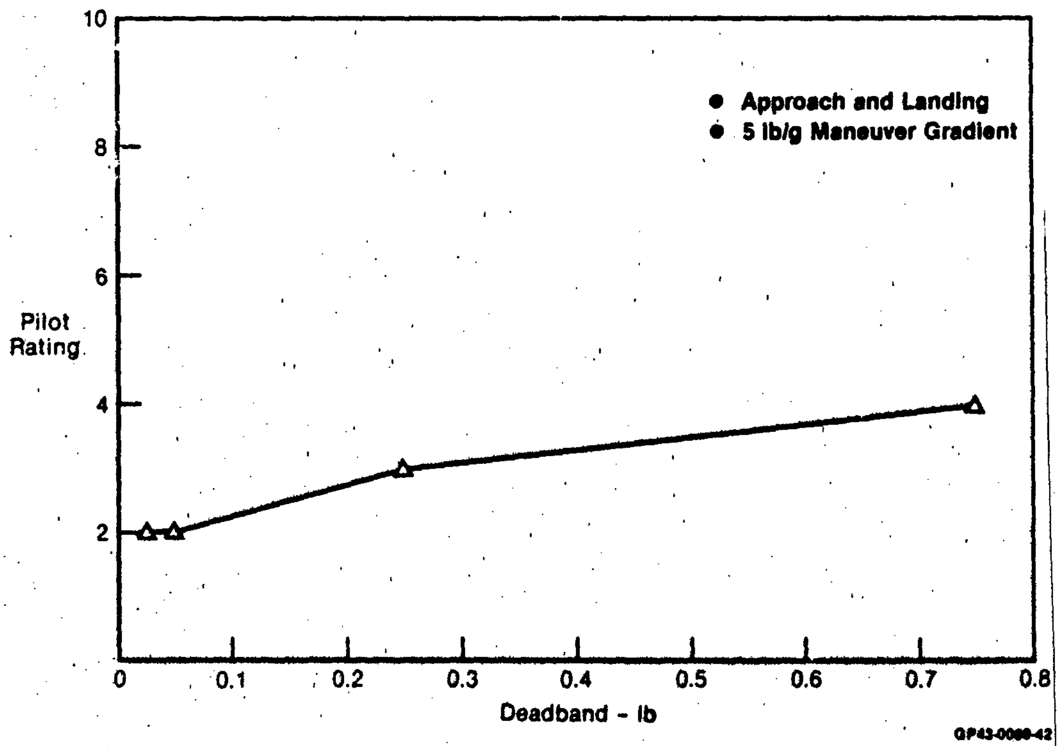

Figure 101. Pilot Rating vs Deadband
Thumb Button Controller   Wings Level Turn   Pilot 12

THUMB BUTTON CONTROLLER - WINGS LEVEL TURN MODE RECOMMENDATIONS: General recommendations for the proper implementation of this type of controller are almost impossible to define. As indicated in the discussion, typical pilot technique is to use the controller to "beep" in corrections in an on-off input strategy. The results of the level target evaluations in the controller simulation indicate that continuous control inputs are possible, however the necessary maneuver gradient characteristics make the controller unsuitable for air-to-ground tasks requiring large, rapid inputs. Additionally, it is doubtful that the controller could be successfully used to control high authority input above 1g in anything but an on-off application. The resulting lateral acceleration characteristics are hypothesized to be detrimental to pilot acceptance of the controller. For these reasons, application of the thumb controller concept is discouraged.

THUMBWHEEL CONTROLLERS - WINGS LEVEL TURN MODE DISCUSSION: Thumbwheel controllers have been examined for various uncoupled control modes in past studies. The principal sources for wings level turn control come from Reference 40 and the controller simulation. In both cases, data is lacking on the exact characteristics.

The thumbwheel used in Reference 40 was mounted on the center stick grip. The axis of rotation was nearly parallel to the stick axis. A spring loaded neutral detent was provided. However, the thumbwheel rotation was not spring loaded to center. Pilot comments indicate this was an undesirable characteristic since the pilot had to physically neutralize the controller to remove any command.

A left hand operated thumbwheel was examined for wings level turn control in approach and landing as part of the controller simulation. The thumbwheel was spring loaded to center and mounted on top of a fixed sidestick-like grip, aft of the throttle. Due to a hardware failure, exact spring constants are unavailable. It was possible to apply full command in one continuous motion with the thumb. Pilot comments were favorable, with one pilot selecting this controller as his second favorite, following the rudder pedals. Only one potential problem was observed. Due to the thumbwheel mounting it was possible for the pilot to place his thumb aft of the thumbwheel (as originally conceived) or on either edge. With the thumb on the aft surface, motions left and right produced right and left wings level turn commands, respectively. If the pilot placed his thumb on the right edge, then pushing forward resulted in a left wing level turn response. One of the pilots commented that it was helpful when he envisioned the thumbwheel as a steering wheel where clockwise rotations resulted in a right turn. The only problem observed was that on ocassion he would place his thumb on the left side of the thumbwheel without realizing it. Thus, when he pushed forward, expecting a left turn, the aircraft responded with a right turn.

THUMBWHEEL CONTROLLER - WINGS LEVEL TURN MODE RECOMMENDATIONS: Further research is needed to clarify specific mechanizations and to establish deadband and maneuver gradient characteristics. The research discussed here does seem to indicate potential usefulness of the controller, at least for small commands. Additionally, the controller simulation results indicate that pilots may not object to additional controllers manipulated by the left hand.

Force deflection characteristics should be such that the controller is self-centering. Because of this, controller rotation limits must be determined so that full command can be applied in one continuous motion with the thumb. Also, the installation should be structured so that only one unambigous direction of input is possible to the thumbwheel.

b. REQUIREMENT: FUSELAGE AZIMUTH AIMING CONTROLLER

Controllers for fuselage azimuth aiming shall meet the following requirements:

- o Breakout/Deadband: __________
- o Maneuver Gradient: __________
- o Force/Deflection Characteristics: __________

DISCUSSION: There are currently no requirements for fuselage azimuth aiming (also called azimuth pointing) mode response dynamics. However, there are existing data from the YF-16 CCV flight test program and controller simulation to develop some reasonable criteria for controller characteristics. Controllers examined included rudder pedals, a twist grip sidestick and thumb buttons. Note that in both studies, automatic implementation with pitch pointing in an integrated fire flight control system was recommended for air-to-air tracking.

RUDDER PEDALS - AZIMUTH AIMING MODE DISCUSSION: The use of rudder pedals to control the azimuth pointing mode was examined in both the YF-16 CCV flight test program and the controller simulation. The YF-16 CCV flight test program results are presented in Reference 46. Available authority in the air-to-air tracking tasks was approximately 4.5 degrees. This yields a maneuver gradient of 11.11 pounds per degree. Breakout and deadband total 15 pounds. Pilot comments indicate that the rudder pedals were less sensitive than a thumb button also examined. A few comments indicate reasonable controllability using the pedals. The azimuth pointing mode was typically matched with thumb button commanded pitch pointing. The major difficulty seemed to be in determining how to successfully blend conventional and pointing commands to produce a tracking solution. The usefulness of the modes was apparent, but the proper technique could not be identified. Pilot comments indicated a preference for automatic implementation.

In the air-to-ground evaluations presented in Reference 46, the rudder pedals seemed somewhat sensitive for fine tracking, especially near full authority. Additionally, the maneuver gradient changed with changing flight condition during a run, thus making response predictability a problem. One pilot observed that nose left commands seemed to move the flight path to the right, requiring more left pedal and so on. This quickly resulted in mode saturation. Inadequate authority was mentioned in some tasks.

The azimuth aiming mode was examined in an air-to-ground strafing task and in approach and landing during the controller simulation. An attempt was made to define an acceptable air-to-air tracking task based on the tasks used in the wings level turn evaluations. After several attempts using the rudder pedals, the pilot commented "it's like trying to integrate the equations of motion in your head." Some benefit for rapid "snap shot" tracking solutions was noted. Based on the comments in Reference 46 and the results of these task definition runs, the air-to-air tracking task evaluations were dropped from the test plan.

The air-to-ground strafing task was initiated from a pop-up maneuver. Three targets spaced 500 feet apart were used. The pilot's task was to obtain four pointing solutions during the pass with the center target being the first and last solution. Ten degrees of pointing were available, with approximately 7 degrees being needed in the task. Mode dynamics were rapid and deadbeat. A complete description of all aspects of the task is given in Volume II.

Pedal displacements of one-half, two, and three inches were examined. A 7 pound breakout was used in all evaluations. Two pilots, 9 and 10, evaluated the half-inch deflection rudder pedals. Their pilot rating results for the maneuver gradient and breakout variations are shown in Figures 102 and 103. A review of the pilot comments indicated that Pilot 10 liked the short pedal throw while Pilot 9 found that the short throw resulted in predictability and sensitivity problems. Only Pilot 9 evaluated various breakouts using the 2.5 lb/deg maneuver gradient. Pilot 10's ratings for the baseline 7 lb breakout case are also shown. Note the marked degradation in Pilot 9's ratings for the 20 lb breakout force.

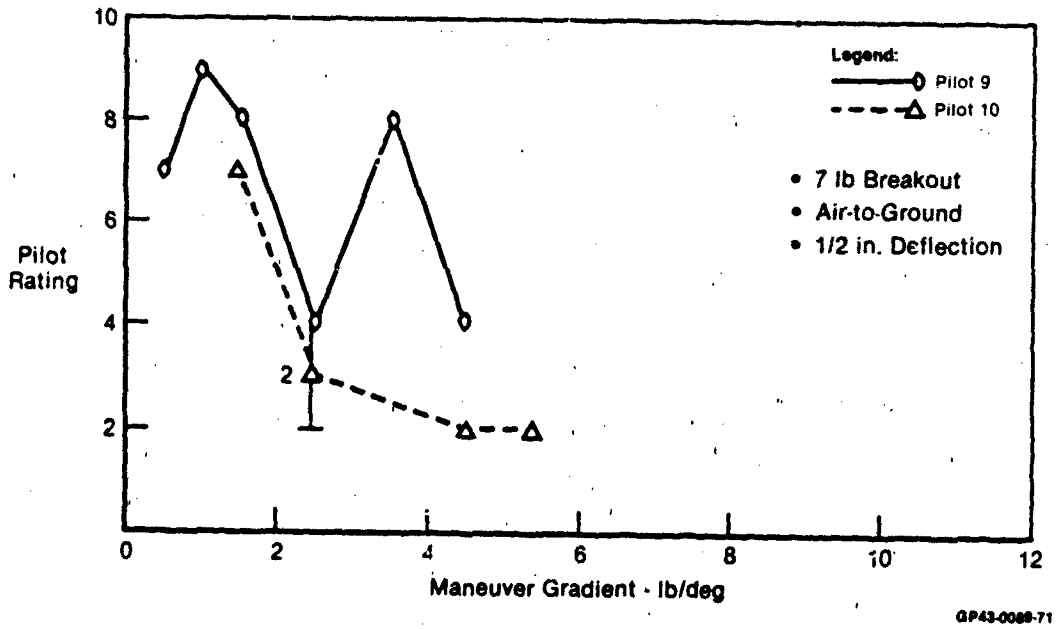

Figure 102. Pilot Rating vs Maneuver Gradient
Rudder Pedals Fuselage Azimuth Aiming

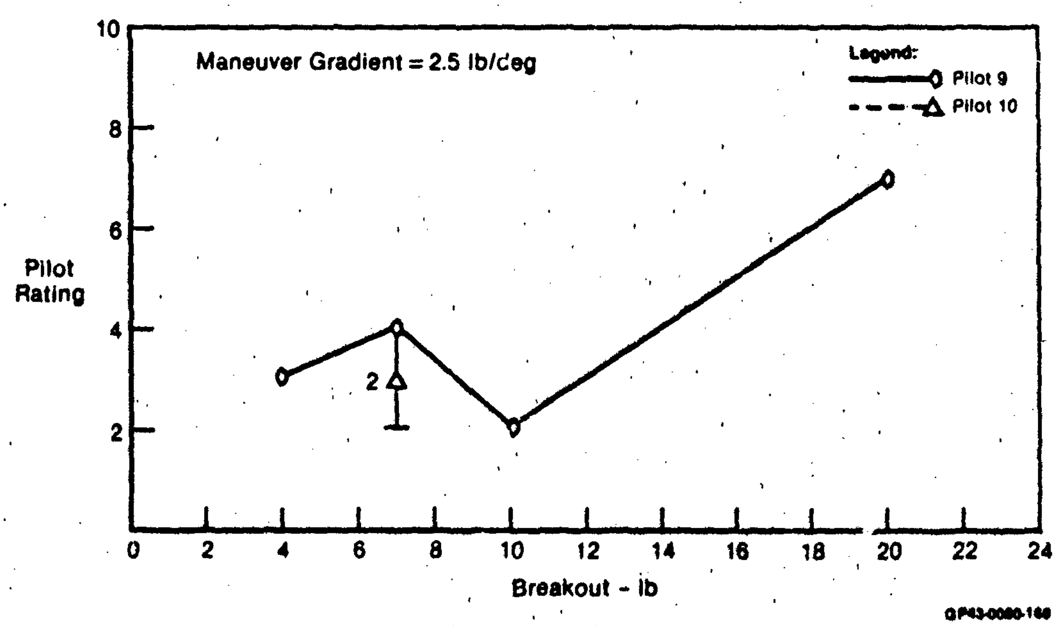

Figure 103. Pilot Rating vs Breakout
Rudder Pedals Fuselage Azimuth Aiming

The situation was reversed for the 3 inch pedal deflections. The pilot ratings from these evaluations are shown in Figure 104. No breakout variations were conducted for this controller. Pilot 10 disliked the larger throw, commenting on a lack of predictability and what seemed to be a slower response. Pilot 9 did not object to the larger throw; he did, however, prefer the two inch pedal deflections. Pilot 9's evaluation of the 4 pounds per degree maneuver gradient indicates some of the effects of pilot learning. This configuration was the first three inch case examined and he assigned it a CH=8. The 10 lb/deg and 6 lb/deg configurations were examined next and given CH=4 and CH=2 respectively. The 4 lb/deg configuration was then reexamined this time receiving a CH=9. The next configuration examined had a maneuver gradient of 8.0 lb/deg. The pilot commented that the forces were a little high at the extremes and assigned a CH=3 commenting that the displacements were fine, the force a little light, and he could accomplish the task in a satisfactory manner. It is felt that this configuration probably represents a borderline case where the pilot was finally able to obtain adequate control after several attempts. Insufficient time was available to perform any breakout variations with the three inch deflection rudder pedals.

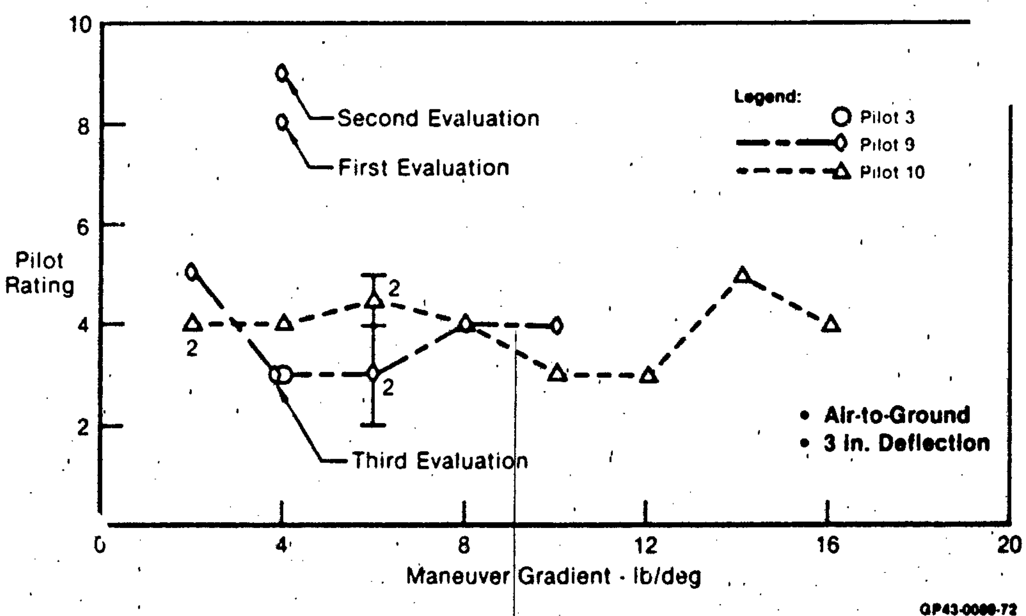

Figure 104. Pilot Rating vs Maneuver Gradient
Rudder Pedals Fuselage Azimuth Aiming

The results of the maneuver gradient variation for the two inch pedal deflections are very interesting. It appears that the only universally acceptable configuration was the ten pound per degree gradient. All configurations shown in Figure 105 had a breakout of 7 lbs. The breakout variation results are shown in Figure 106. Note the rapid degradation exhibited by some pilots on either side of the 10 lb/deg gradient. It is unclear what caused the dispersion in Pilot 9's ratings.

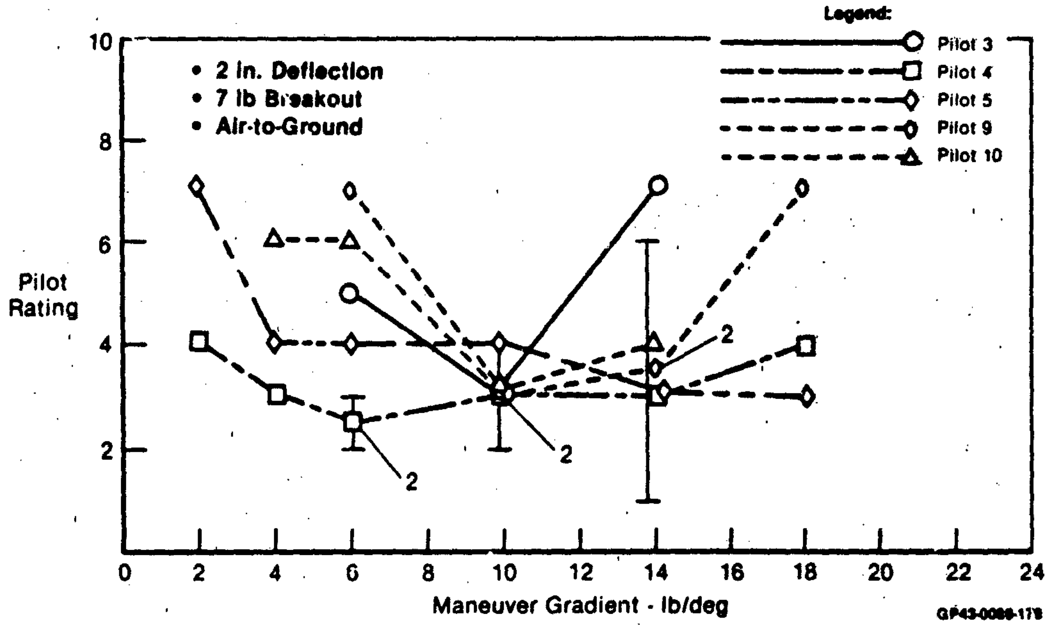

Figure 105. Pilot Rating vs Maneuver Gradient
Rudder Pedals Fuselage Azimuth Aiming

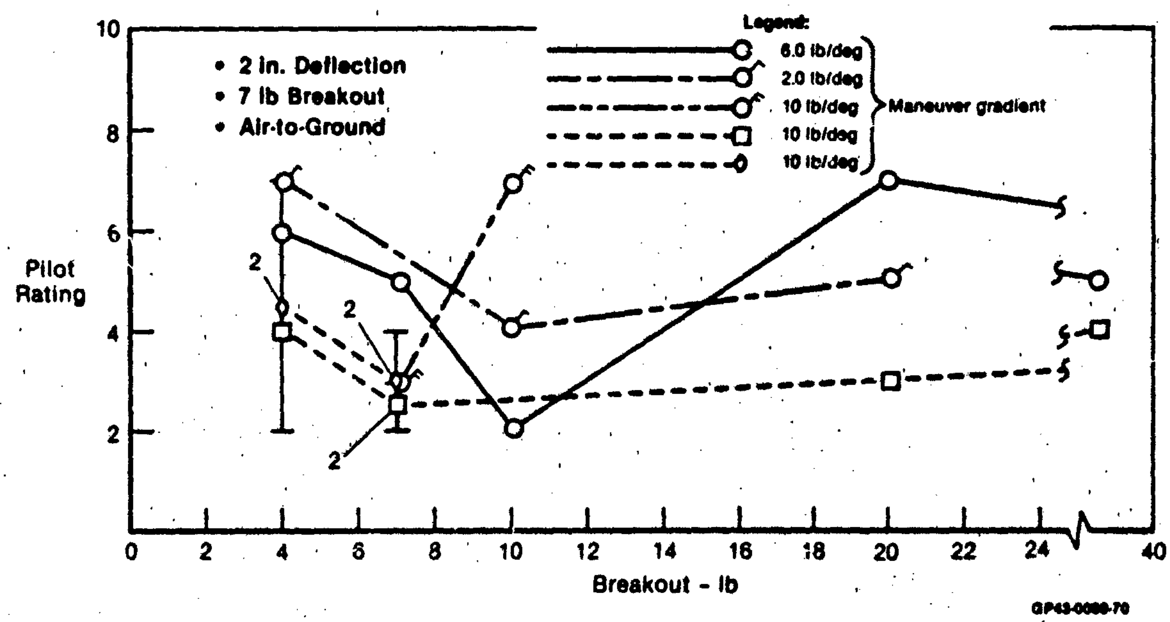

Figure 106. Pilot Rating vs Breakout
Rudder Pedals Fuselage Azimuth Aiming

An interesting trend was noted in the breakout variations for Pilot 3. For this pilot, it appears that the influence of breakout variations is highly dependent on the maneuver gradient used. This pilot appears to be more sensitive to breakout as the maneuver gradient is increased. Unfortunately, pilot scheduling problems and a simulator hardware failure prevented further evaluation at the 10 lb/deg maneuver gradient level. Except at the extremes of 4 and 38 lb of breakout, Pilot 4 appears to be insensitive to breakout variations.

The approach and landing/fuselage azimuth aiming results are presented in Figure 107. The azimuth aiming mode was used to maintain fuselage orientation down the runway despite the necessary crosswind corrections. This significantly reduced or eliminated the large crab angles at touchdown that were evident in the wings level turn evaluations. With the two inch deflection pedals, satisfactory results were obtained over the range from 2 to 6 pounds per g. Pilot 7's ratings are viewed with some skepticism since they are based on limited practice during task development evaluations. Pilot 14 indicated dissatisfaction with the half inch pedal deflection. He indicated a general loss in precision of his control inputs. All configurations had an authority of 6.7 degrees of pointing.

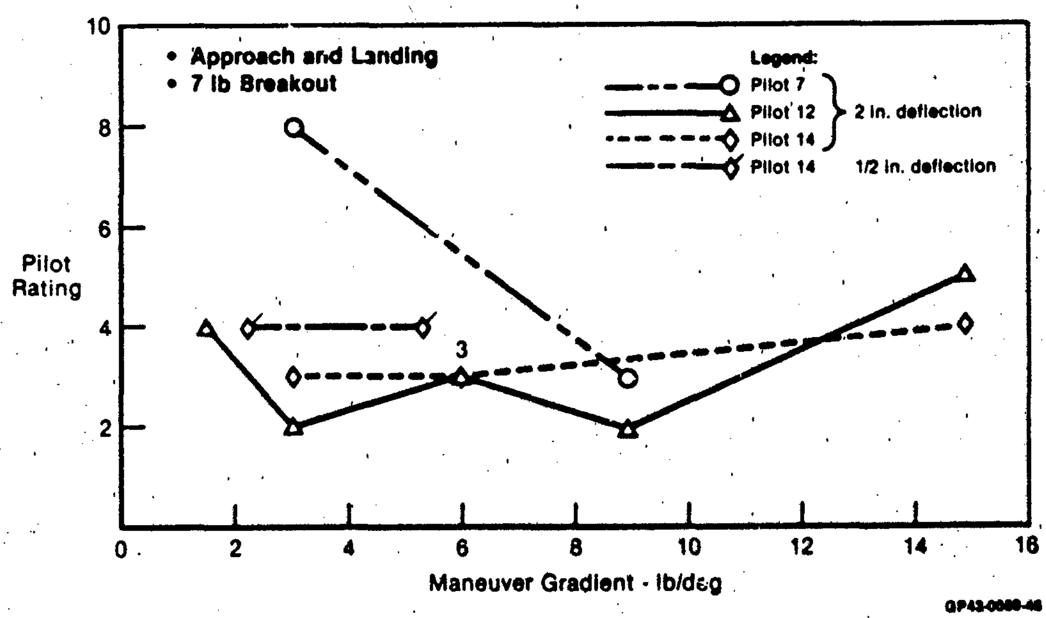

Figure 107. Pilot Rating vs Maneuver Gradient
Rudder Pedals Fuselage Azimuth Aiming

RUDDER PEDALS - AZIMUTH AIMING MODE RECOMMENDATIONS: The recommended ranges of values for this requirement are:

Breakout	- between 1 and 7 pounds
Maneuver gradient	- between 8 and 12 pounds per degree
Deflection	- no recommendation (see text)

When specifying characteristics for rudder pedals for this mode, two items must be remembered. The simulation evaluations indicated that a high degree of proficiency appears to be required to use the mode. Also, there again seems to be a definite relationship between breakout force and maneuver gradient.

Breakout forces are recommended to be between 1 and 7 pounds as were the wings level turn requirements. While this is not totally supported by the data, it is proposed so as to be consistent with the wings level turn requirements. This range of values should not be overly restrictive or cause difficulties in compliance.

Maneuver gradient should be between 8 and 12 pounds per degree based on the two inch pedal deflection data from the simulation. Based on the YF-16 CCV information, gain scheduling should be used to minimize variation in maneuver gradient with flight condition. Note that the YF-16 CCV maneuver gradient of 11.11 degrees falls in the acceptable range. Pilot comments were not strongly negative about the maneuver gradient, only the variation. Additionally, at least one pilot indicated that practice would improve his ability to utilize the mode.

Deflection characteristics will not be specified. More data is necessary before a requirement can be given. However, a value of 2 inches for the maximum deflection is recommended based on the simulation results. The use of some deflection was shown to improve predictability of response. Too much deflection was shown to result in somewhat laggy response characteristics.

It is important to note that these requirements are based mainly on the simulation results. The mode response dynamics were not varied. There is little or no data available to specify whether the simulation dynamics are near optimum.

TWIST GRIP CONTROLLER - AZIMUTH AIMING MODE DISCUSSION: In the controller simulation, the twist grip was also examined for application to control of the azimuth aiming mode. The controller was examined in the air-to-ground and approach and landing tasks.

The pilot rating data for the air-to-ground task is presented in Figures 108 and 109. The maneuver gradient variations are shown in Figure 108. The most universally acceptable gradient is at the 3.6 inch-pound per degree level. This controller was not as well liked as the rudder pedals. Several cases of pitch and roll coupling were noted using this controller. The reader is referred back to the coupling discussion in the wings level turn section for a detailed examination of this phenomenon. No definitive trends were noted in the deadband variation shown in Figure 109. As noted in the wings level turn discussion, the best use of deadband is to reduce cross-axis inputs from the conventional controller.

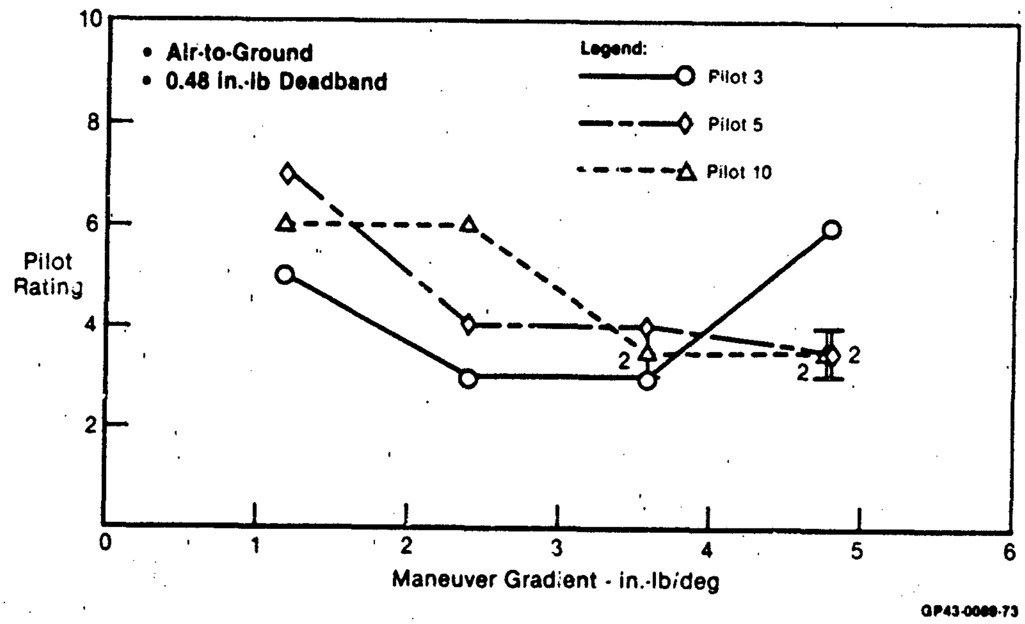

Figure 108. Pilot Rating vs Maneuver Gradient
Twist Grip Sidestick   Fuselage Azimuth Aiming

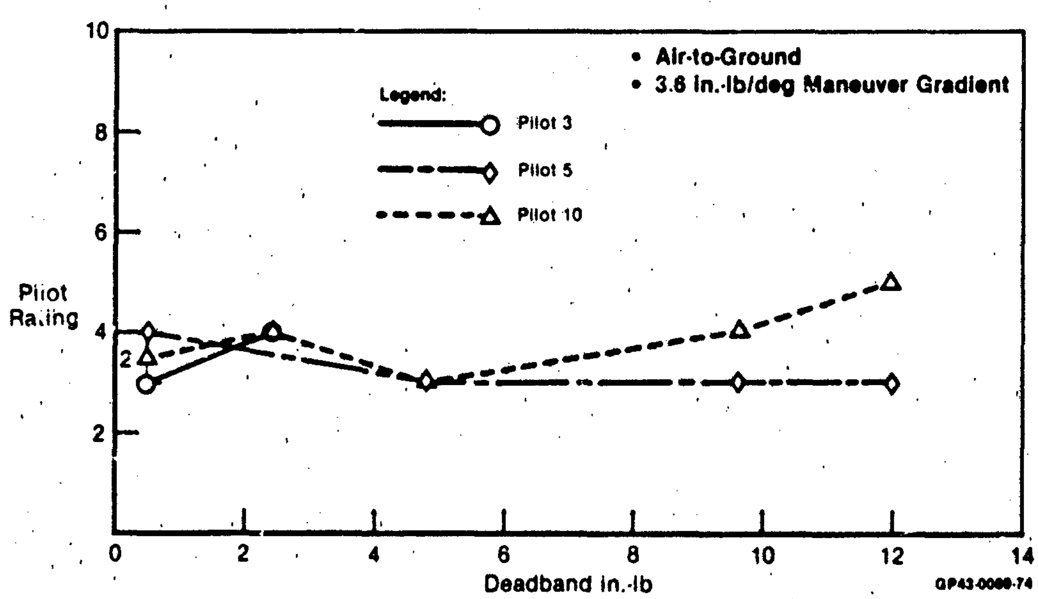

Figure 109. Pilot Rating vs Deadband
Twist Grip Sidestick   Fuselage Azimuth Aiming

Pilot 12 examined the twist grip/azimuth aiming combination in the approach and landing task. The pilot rating results are presented in Figure 110. The resulting poor ratings are the result of the pilot's inability to control the conventional response immediately prior to touchdown while holding in a twist command. No acceptable pilot ratings were collected during this evaluation.

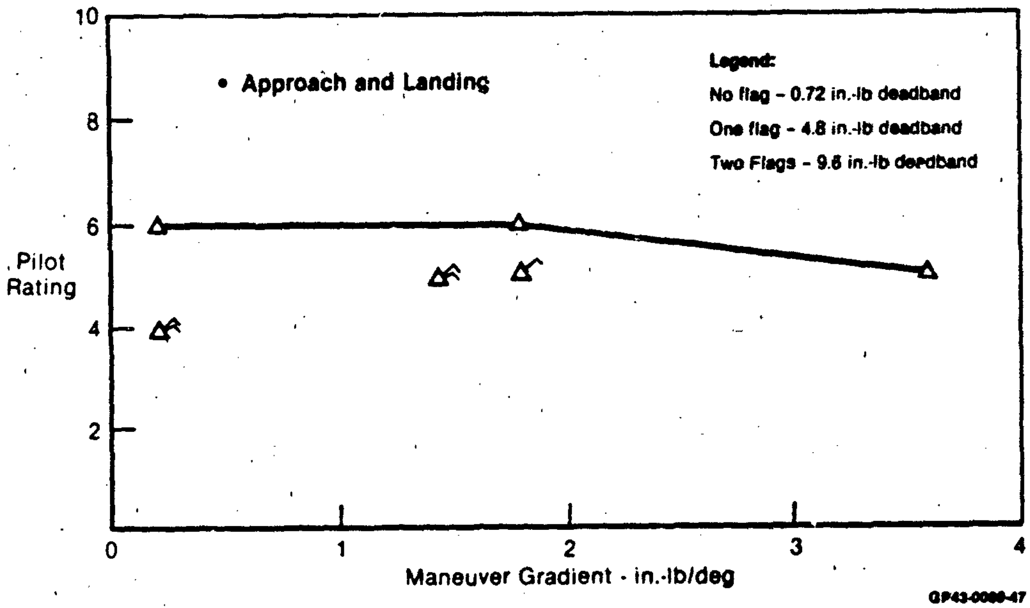

Figure 110. Pilot Rating vs Maneuver Gradient
Twist Grip Sidestick Fuselage Azimuth Aiming **Pilot 12**

TWIST GRIP CONTROLLER - AZIMUTH AIMING MODE RECOMMENDATIONS: The following values have been identified as being potentially acceptable for this mode/controller combination:

Deadband	- 5 inch-pounds
High speed maneuver gradients	- between 3 and 4 inch-pounds per degree
Low speed maneuver gradients	- no recommendation (see text)
Deflection	- 8 degrees with solid stops

Note: Ranges of acceptable values could not be determined.

Typically, the twist grip was not as well liked as the rudder pedals for control of azimuth aiming. For recommendations on deadband and control grip shape the reader is referred to the discussion in the wing level turn section. The discussion on increased control deflection is also considered applicable to use with the azimuth aiming mode. In the air-to-ground task, the preferred maneuver gradient was in the range between 3 and 4 inch-pounds per degree. As in the rudder pedal case, it is recommended that the variations of gradient with changing flight condition be minimized. No recommendations are given for the approach and landing task. The primary problem mentioned was the requirement to tightly grip the stick to make twist inputs, thus reducing sensitivity in the other control axes. A redesign of the stick grip to facilitate twist inputs may reduce this problem. Additional research is also needed to quantify the effects of mode dynamics.

<u>THUMB BUTTON CONTROLLERS - AZIMUTH AIMING MODE DISCUSSION:</u> Thumb button controllers for the azimuth aiming mode were examined in the YF-16 CCV flight test program and in the controller simulation. In the flight test report of Reference 46, the authority in the air-to-air and air-to-ground tasks was approximately 4.5 degrees. Maximum button input force was 3.1 pounds with a 0.11 pound deadband. The resulting maneuver gradient was 0.667 pound per degree. During testing, elevation aiming was usually present on the other axis of the button. The deadband in this axis was also 0.11 pound. There is some mention of button cross-axis coupling in the pilot comments. The azimuth aiming axis was generally felt to be too sensitive. Also, since the azimuth authority was twice the elevation authority, there was a lack of harmony between the axes. In the air-to-air tasks, the pilots generally indicated that the mode would best be implemented as part of an integrated flight-fire control system with the system determining pointing inputs with the available authority limits.

In the controller simulation, Pilot 10 evaluated the thumb button controller for use with the azimuth pointing mode. These results are presented in Figure 111. As indicated, no acceptable maneuver gradient could be found which had enough authority to accomplish the full task. It is estimated that an acceptable gradient may occur somewhere beyond the one pound per degree level. These results are easily understood if the reader recalls the pilot techniques adopted by Pilot 6 in the wings level turn evaluation. Pilot 6 indicated that the best use of the button was as an on-off type command during the azimuth aiming tasks since it requires continuous commands. Based on these results, attempts to control the azimuth aiming mode with this controller were abandoned.

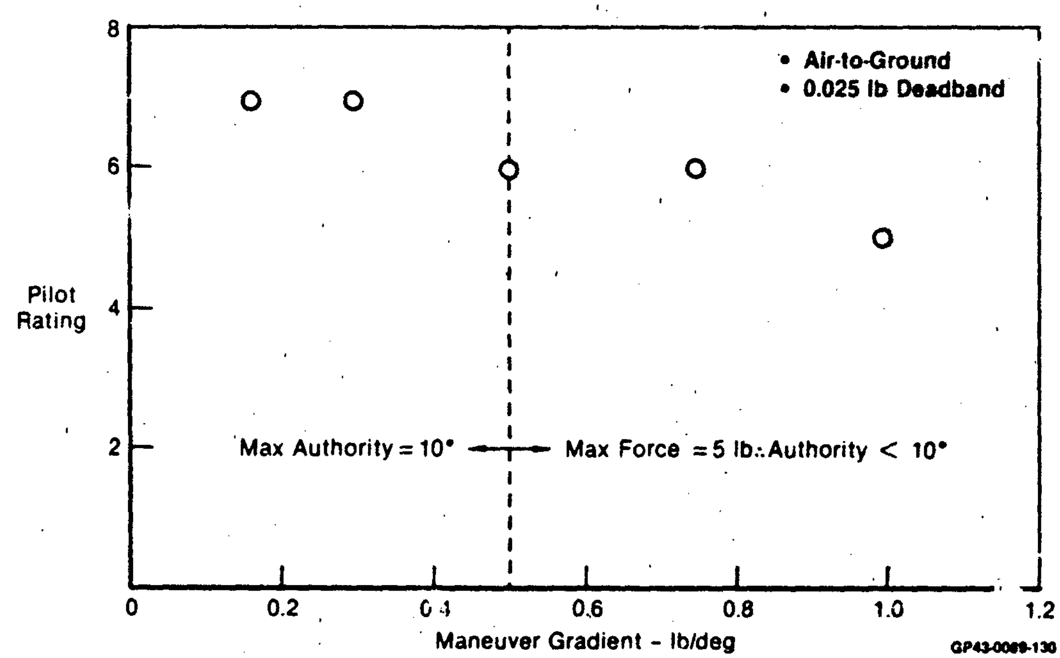

Figure 111. Pilot Rating vs Maneuver Gradient
Thumb Button Controller Fuselage Azimuth Aiming Pilot 10

<u>THUMB BUTTON CONTROLLER - AZIMUTH AIMING MODE RECOMMENDATIONS</u>: As in the case of thumb button control for wings level turn, the use of a thumb button to control azimuth aiming is discouraged, particularly in the case of proportional control of aiming angle.

c. <u>REQUIREMENT: LATERAL TRANSLATION CONTROLLER</u>

Use of the primary lateral translation controller shall not require use of another control manipulator to meet the lateral translation bandwidth requirement. Additionally, the controller characteristics shall be:

Breakout/Deadband: ________
Maneuver Gradient: ________
Force/Deflection Characteristics: ________

DISCUSSION: The requirement for prohibiting the use of additional controllers to meet the bandwidth requirement was taken from Reference 68, Section 3.7.1 C). The characteristics identified have been shown to have a definite impact on pilot acceptance of other control modes. The controllers examined in this section include rudder pedals, twist grip sidestick, thumb buttons and a throttle mounted finger lever.

RUDDER PEDALS - LATERAL TRANSLATION MODE DISCUSSION: The primary sources of information concerning the use of rudder pedals to control lateral translation were References 26, 44 and 46 and the controller simulation.

In Reference 44, two types of lateral translation modes were investigated in a dive bombing task. Design criteria were derived for each mode. The pilot commanded a rate of sideslip angle change in the lateral translation - integral (LT-I) mode. In this mode the pilot commanded a lateral acceleration. When the input was removed, the aircraft remained at a constant translation velocity. The response was much like a wings level turn response in that the velocity vector could be placed very accurately, the difference was the absence of any change in aircraft heading. Due to the similarities, roughly the same controller sensitivities and mode authorities were recommended. The maximum recommended maneuver gradient was 110 pounds per g with the minimum gradient specified at 20 pounds per g. The recommended design goal was 38.5 pounds per g and an authority of 1g.

The lateral translation - proportional (LT-P) mode examined in Reference 44 was a sideslip angle command system with no change in aircraft heading. In this mode the pilot commanded a sideslip angle. When the command was removed, the sideslip angle returned to zero. Note that in the LT-I and LT-P modes an advanced bombsight was used which assumed the stores would descend along the velocity vector. As a result, the pipper was displaced laterally on the head up display whenever a sideslip was present. The pilot's task was to place the pipper on target and maintain the solution until the proper release conditions were obtained. Once the pilot rolled out and began the dive, the target stayed essentially fixed on the forward field of view. The pilots then moved the pipper to the target, using rate commands in LT-I and displacement commands with LT-P. In the sense of putting the pipper on the target, the LT-P mode bears a strong resemblence to the azimuth aiming mode. The observed results are remarkably similar. The maneuver gradient appeared to be strongly related to the response dynamics. The response dynamics were characterized as second order in nature and design requirements were specified accordingly. The minimum recommended maneuver gradient was 6 pounds per degree when the damping ratio was less than 1.2. A maximum maneuver gradient of 17 lb/deg and a minimum authority of 3 degrees was also specified along with a 0.5 g lateral acceleration authority. The recommended design maneuver gradients were 7 pounds per degree for damping greater than 1.2 and 10 pounds per degree for damping less than 1.2. A design guideline of 4.5 degrees and 1g lateral acceleration capability was also recommended.

The YF-16 CCV flight test results of Reference 46 indicate that the translation mode was examined primarily in air-to-ground weapon delivery tasks. Approximately 4.5 degrees of sideslip authority was available. The resulting pedal maneuver gradient was approximately 11 pounds per degree. Pedal breakout and deadband totalled 15 pounds. No serious comments were noted concerning the pedal sensitivity. The overwhelming majority of comments dealt with the slowness with which the response was achieved. Additionally, once the desired translation had been made and the input removed, the slow response characteristics allowed the plane to drift past the desired flight path. One pilot adopted the technique of using opposite commands to more rapidly stop the aircraft when desired. Because of the slow response, the usefulness of the mode was questionable.

The use of the rudder pedal/lateral translation mode was investigated in the controller simulation. The mechanization was such that a sideslip angle proportional to pedal input was developed at a fixed aircraft heading. A headwind shearing to a crosswind and atmospheric turbulence models were used to excite the aircraft. Pilot comments indicate that the lateral translation mode was somewhat confusing and not well liked by either of the evaluation pilots. These comments are apparent in the pilot rating data shown in Figures 112 and 113. Due to these problems, it is felt that no useful trends or recommendations can be derived from these plots or the pilot comments in terms of controller requirements. It is not clear what caused the problems. One possible reason may be the combination of relatively slow response combined with the constantly changing requirements imposed by the shear. It is recommended that future applications of lateral translation in approach and landing tasks consider wind shears in addition to steady crosswinds.

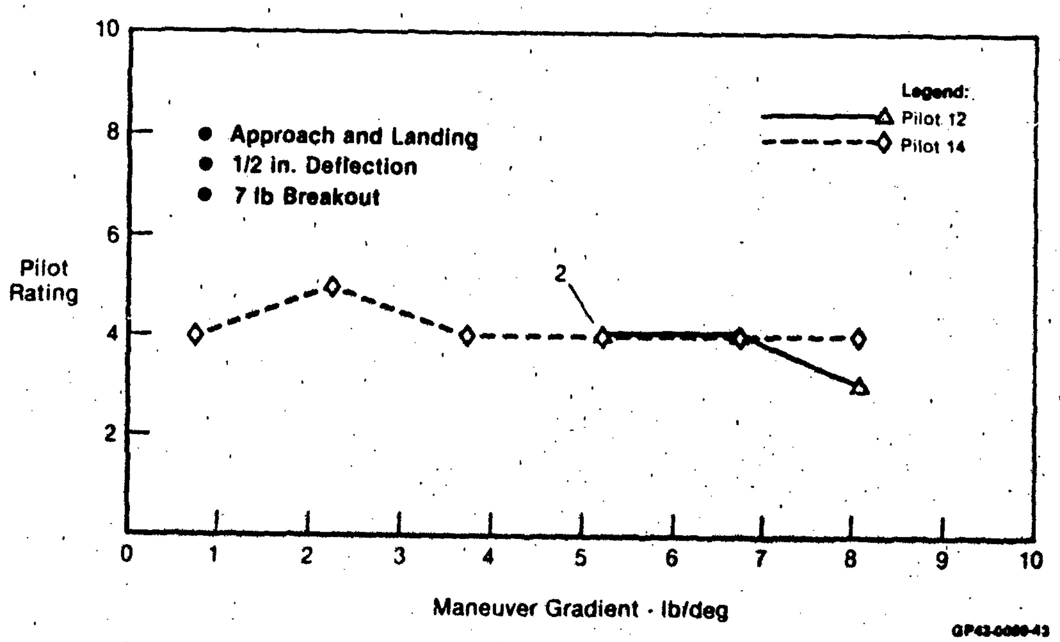

Figure 112. Pilot Rating vs Maneuver Gradient
Rudder Pedals Lateral Translation

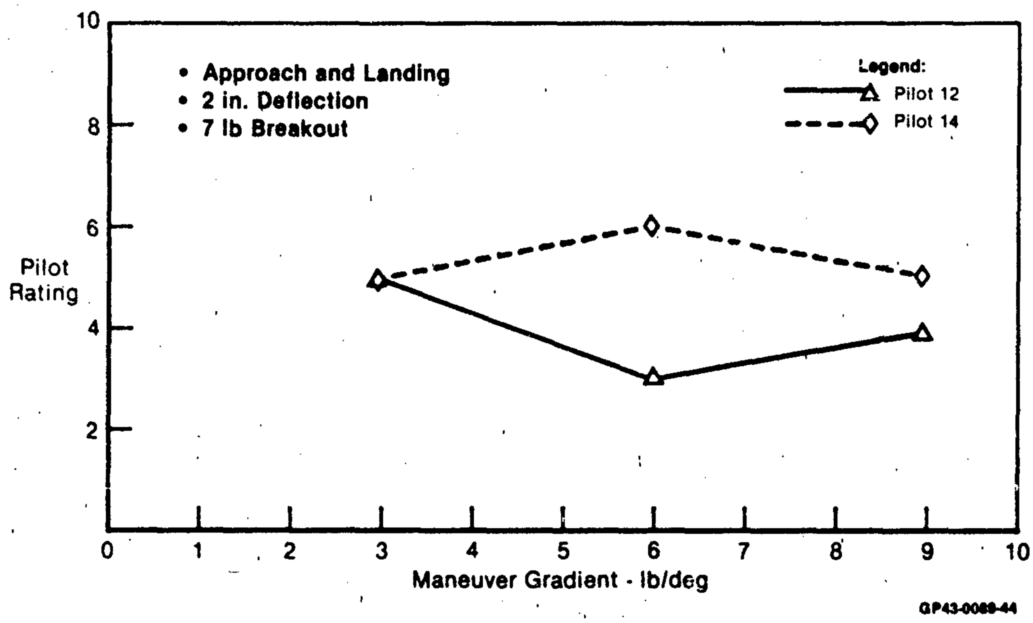

Figure 113. Pilot Rating vs Maneuver Gradient
Rudder Pedals Lateral Translation

<u>RUDDER PEDALS - LATERAL TRANSLATION MODE RECOMMENDATIONS:</u> The recommended ranges of values for this requirement are:

Breakout	-	between 1 and 7 pounds
High speed maneuver gradient	-	between 6 and 17 pounds per degree (for proportional control)
		between 20 and 110 pounds per g (for integral control)
Low speed maneuver gradient	-	none recommended (see text)
Deflection	-	none recommended (see text)

Based on the findings of the controller simulation, no recommendations are given for maneuver gradient in the approach and landing task. However, it should be noted that if the mode is to be used to cancel a steady crosswind, the maneuver gradient used for a proportional mode must not result in prolonged high pedal forces which may be objectionable to the pilot. Additionally, it is recommended that future efforts consider the impact of windshear on mode acceptability.

The maneuver gradient requirements of Reference 44 are adopted for air-to-ground use of lateral translation. These are:

- Proportional control modes
  - o 17 lb/deg Maximum
  - o 6 lb/deg Minimum
- Integral control modes
  - o 110 lb/g Maximum
  - o 20 lb/g Minimum

The data of Reference 46 tend to support these guidelines. Additionally, the recommended design goals are considered to be adequate.

Breakout forces shall be between 1 and 7 pounds. While data to support this is lacking, these limits are consistent with previous recommendations for rudder pedal controllers. The pedals used in Reference 44 were configured with a 7 pound breakout. The problems noted with mode usage in Reference 46 cast some doubt as to the impact of the 15 pound breakout on overall mode acceptability.

No requirements are given for controller deflection. The pedals of Reference 44 had a maximum deflection of 2.5 inches. As indicated in the wings level turn and azimuth aiming sections, the use of moderate deflections is felt to have some benefit in improving predictability of mode response.

<u>TWIST GRIP CONTROLLERS - LATERAL TRANSLATION MODE DISCUSSION:</u> Due to the lack of pilot acceptance of the translation mode as indicated by the comments and ratings shown in Figure 114, no recommendations are given. The reader is referred to previous discussion of this controller in the wings level turn and azimuth aiming sections for discussions concerning deadband and recommended deflection characteristics.

<u>THUMB BUTTON CONTROLLERS - LATERAL TRANSLATION MODE DISCUSSION:</u> Lateral translation commanded by a thumb button controller was examined in the YF-16 CCV flight test program (Reference 46). However, it is felt that mode response characteristics may have masked any serious controller deficiencies. In addition, based on the comments on control coupling in the wings level turn and azimuth aiming sections, use of this controller is not recommended.

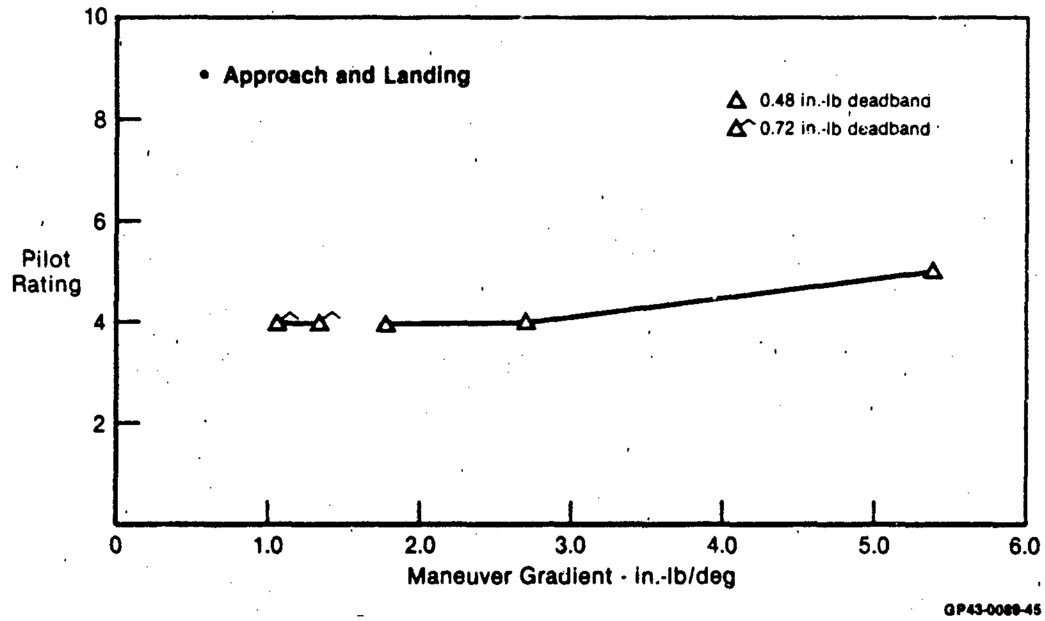

Figure 114. Pilot Rating vs Maneuver Gradient
Twist Grip Sidestick Lateral Translation Pilot 12

FINGER LEVER CONTROLLER - LATERAL TRANSLATION MODE DISCUSSION: A finger operated lever mounted on the throttle grip of an F-8 was examined as a lateral translation controller in Reference 42. The controller was operated by the tip of the left hand index finger. A complete description of the controller is given in the report. The evaluation task was approach and landing. No recommendations are given here since it is felt that delays in the response characteristics of the mode probably masked the controller characteristics. It is interesting to note that the pilots did not object to a throttle-mounted controller.

d. REQUIREMENT: VERTICAL PATH CONTROLLER

Controllers for vertical path control shall meet the following requirements:

- o Breakout/Deadband: ________
- o Maneuver Gradient: ________
- o Force/Deflection Characteristics: ________

DISCUSSION: This requirement is included for completeness. There is little supporting data to generate recommendations. The characteristics stated in the requirement have been identified as important in successful implementation of other controllers.

The majority of available data comes from reference 46, the F-16 CCV flight test program. Potential uses for the vertical path control mode were identified in both air-to-air and air-to-ground tasks. However, a review of the reference tends to indicate that use of a stick-mounted thumb button controller detracted from the mode evaluations. Cross-axis coupling problems were noted when a lateral CCV mode was available on the button. Problems were also noted in using the thumb button in conjunction with simultaneous pitch inputs, particularly elevated sidestick force levels.

These problems are not apparent in the discussion of vertical path control (direct lift) presented in Reference 74. The twist grip throttle was used for mode control. The reference indicates the pilots could quickly and smoothly use direct lift to bring the bomb impact point into the target during bombing tasks. The transition between twist throttle control and conventional stick was apparently quite easy. This indicates the benefit of removing additional control tasks from the conventional controller as noted in previous discussions for other controller/mode combinations.

e. REQUIREMENT: FUSELAGE ELEVATION AIMING CONTROLLER

Controllers for fuselage elevation aiming control shall meet the following requirements:

- Breakout/Deadband: ________
- Maneuver gradient: ________
- Force/Deflection Characteristics: ________

DISCUSSION: This requirement is included for completeness. The characteristics identified in the requirement have been found important to successful implementation of other controller/mode combinations. However, there is little supporting data to generate recommendations.

The F-16 CCV Flight test program (Reference 46) provides the majority of available information. As indicated in the vertical path control discussion, potential uses for the elevation aiming (also identified as pitch pointing or elevation pointing) mode were identified by the pilots. A review of the pilot comments in the reference indicates that in air-to-air tracking it was difficult to simultaneously command pointing inputs from the thumb button controller and conventional pitch inputs from the sidestick. Most evaluations appear to have resulted in limited use of the mode or application of full nose up pointing command with primary tracking done using the conventional sidestick. The primary use for the mode in air-to-ground tasks was in increasing clearance altitude during strafing runs. Two techniques were examined. One involved applying full nose down command and then using conventional sidestick control. The pilots found it uncomfortable to hold the button input and move the stick. The other method involved establishing a dive path aiming above the target and the use of the elevation aiming in a continuous fashion to maintain the pipper on the target. This technique worked fairly well and was better appreciated by the pilots. Control sensitivity seems to have been satisfactory. The controller characteristics are estimated to have been 1.2 pounds per degree maneuver gradient with a 0.11 pound deadband. The maximum button input force was 3.1 pounds and the estimated authority was 2.5 degrees. Note, however, that coupling problems were still observed on several runs when an additional mode was available on the button lateral axis.

The AFTI/F-16 pointing mode evaluated in the air-to-air tracking task was an integral mode. The flight test results are reported in Reference 74. In this type of control implementation, the pilot's input commands a pointing angle rate of change. The discussion in the reference indicates that the pilots felt the maximum rate of 2 degrees per second was too slow. Additionally, they would have liked more pointing authority. The twist throttle was used as the pointing controller. The reference indicates the pilots felt it was difficult to integrate pitch stick and throttle twist simultaneously against a dynamic target. However, the pilots indicated that, through training, satisfactory results could be obtained. The reference also states that some pilots felt a pointing angle command system might be preferable to the pointing rate command system tested.

f. <u>REQUIREMENT: VERTICAL TRANSLATION CONTROLLER</u>

Controllers for vertical translation shall meet the following requirements:

- o Breakout/Deadband: __________
- o Maneuver Gradient: __________
- o Force/Deflection Characteristics: __________

DISCUSSION: The use of vertical translation for control of flight path has been examined in a number of studies. In many of these studies, the translation was often commanded from the conventional pitch axis controller, either in a blended fashion or with the normal function disconnected. For these applications, the requirements for the conventional controller shall apply. Maneuver gradient values should then be examined in ground-base and in-flight tests to provide reasonable control sensitivities.

Several studies have examined the control of vertical translation from manipulators other than conventional controllers. However, in general, there is insufficient data to develop specific requirements. In the following discussion several controllers will be examined for their acceptability to the evaluation pilots.

THUMBWHEEL CONTROLLERS - VERTICAL TRANSLATION MODE DISCUSSION: References 36, 37, 38 and 39 examined thumb wheel controllers for use in carrier approach and landing tasks. In all cases, the results indicate an improvement in flight path control capability near touchdown. Three of the studies, References 36, 38 and 39, examined the use of the thumb to make on-off (or "bang-bang") type control inputs in which full up or down or off were the only inputs available. In all cases, this was found inferior to proportional control using the thumbwheel. However, it was noted in all studies that the pilots tended to make on-off type inputs with proportional control. This may be due to some perceived optimal control technique developed by the pilots, who also wanted the ability to make fine, proportional inputs available. The thumbwheel used in the Reference 38 and 39 evaluations of an F-8 aircraft was mounted on the left side of the centerstick control grip. Rotation was about a horizontal axis. The thumbwheel was spring loaded to center and had ±30 degrees of rotation available. Control authority was approximately 0.12 g upward and 0.1 g downward. No adverse comments for the controller installation were noted.

THUMB BUTTON CONTROLLERS - VERTICAL TRANSLATION MODE DISCUSSION: Thumb button control of vertical translation was examined in the YF-16 CCV flight test program reported in Reference 46. The pilot comments on use of the mode in the air-to-ground task were mixed and inconclusive with the mode only being used in a skip bombing task. Flight path angle changes of ±2.5 degrees were available; however, it is felt that the relatively slow response characteristics probably overshadowed the controller characteristics.

HEAVE AXIS CONTROLLER - VERTICAL TRANSLATION MODE DISCUSSION: A heave axis was incorporated in the sidestick used in the controller simulation. Limited evaluations of its use in controlling vertical translation in the approach and landing task were conducted. Pilot acceptance of the controller was poor. One pilot in particular complained of coupling between conventional pitch inputs and heave inputs, particularly during flare. Further testing would be required to develop specifications. However, based on the available information, use of this type of controller is not recommended.

TWIST THROTTLE CONTROLLER - VERTICAL TRANSLATION MODE DISCUSSION: A twist grip throttle similar to the controller employed in AFTI/F-16 was used in limited evaluations of vertical translation in the approach and landing task of the controller simulation. Exact characteristics tested are unavailable and would be of limited use due to the small number of evaluations. This controller was highly accepted by both evaluation pilots who examined it. Both pilots felt the controller was natural and an improvement over adding an additional control axis to the conventional controller. Benefits in reduced touchdown point dispersion and finer control of sink rate at touchdown were predicted by both pilots.

In the discussion of the flight test results of the AFTI/F-16 presented in Reference 74, there is no mention of pilot acceptance of the twist throttle for this mode. The majority of pilot comments seemed to deal with problems in mode implementation.

SECTION VI
CONCLUSIONS AND RECOMMENDATIONS

The primary purpose of this effort was to develop design guidelines for controllers for uncoupled aircraft motion. The guidelines presented here apply not only to uncoupled motion controllers; many of them can be extended to the design of any cockpit controller. The qualitative requirements presented in Volume 1 and the observations made during the simulation presented in Volume 2 are felt to define many of the basics involved in controller design. Additionally, the quantitative requirements presented in Volume 1 give some guidance based on past controller implementations.

However, there is a shortage of data pertaining to the design of controllers for uncoupled motion. The simulation results presented in Volume 2 illustrate the impact controller characteristics can have on the acceptability of fixed response dynamics. It is probably true that response dynamics can have an effect on the acceptability of a fixed set of controller characteristics. Further research is required to quantify the impact of response dynamics on controller requirements. One area not addressed by this effort is the impact of controller dynamics on pilot opinion. Every controller examined can be characterized as a spring-mass-damper system. The best that can be said at this point is the controller dynamics shall not be detrimental to pilot acceptance of a configuration.

Future high authority systems will require the use of non-linear maneuver gradients to allow efficient implementation. Current research has shown that non-linear gradients can enhance the precision of many responses. The use of digital computers in advanced flight control systems makes implementation of non-linear command gradients relatively straightforward. Guidelines for the shaping of non-linear gradients remain to be developed.

The integration of automatic and manual flight control also needs to be examined in more detail. The results of several studies indicate the fuselage pointing modes should be an automatic feature of an integrated fire/flight control system. Are there other modes which would be beneficial as part of an automatic system? Those areas requiring manual control must be defined and specific techniques for mode usage must be investigated. Benefits have been observed for different modes in different tasks, but the impact on total mission capability remains to be defined.

Many of these areas can be addressed by ground-based simulation. However, eventually flight testing is required. In-flight evaluation provides the pilot with many cues as well as a different mental attitude than can be developed in a ground-based simulator. Many of these problems may be addressed by further testing using the AFTI/F-16 and future in-flight simulators.

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